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**FLUTTER TEST
OF AN ARRAY OF FULL-SCALE PANELS
FROM THE SATURN S-IVB STAGE
AT TRANSONIC MACH NUMBERS**



T. M. Perkins

ARO, Inc.

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Letter dtd 26 April 73.

February 1968

*signed by William
O. Cole.*

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*Letter dtd 26 April '73
Signed by William O. Cole*

FOREWORD

The work reported herein was performed at the request of the National Aeronautics and Space Administration (NASA), Marshall Space Flight Center (MSFC) under Program Area 921E, Project 9240.

The results of the test presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Contract AF40(600)-1200. The tests were conducted from August 24 through September 7, and October 31 through November 6, 1967, under ARO Project No. PT1858, and the manuscript was submitted for publication on January 2, 1968.

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This technical report has been reviewed and is approved.

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Director of Test

ABSTRACT

Flutter characteristics of a 30-deg segment of the full-scale Saturn S-IVB stage were obtained at Mach numbers from 1.30 to 1.60 for various combinations of axial-compressive loads and panel differential pressures. Flutter was encountered in one or more panels when sufficient axial load was applied to either partially or completely buckle the panels. The flutter was amplitude limited, and no structural failures occurred on any of the panels as a result of flutter. However, the test had to be terminated when two panels in the fifth bay were statically buckled beyond their elastic limit and permanent deformation resulted. A calibration test was conducted prior to the flutter test to determine the optimum design of the fixture used to support the model. Also static-pressure and boundary-layer surveys were made on the model at tunnel conditions comparable to those of the flutter phase.

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NOMENCLATURE

BLR	Boundary-layer rake
C_p	Pressure coefficient, $\frac{p_n - p_\infty}{q_\infty}$
D_n	Total pressure orifices on wake rake, Fig. 6
L	Pressure panel length, in. (Fig. 9a)
L_{F1}	Calibration model length, in. (Fig. 5a)
L_{F2}	Calibration model length, in. (Fig. 5b)
ℓ_{1-5}	Panel length in each of five bays, in. (Fig. 9b)
M_∞	Free-stream Mach number
P_{cr1-3}	Critical buckling load for each bay, lb
P_{HT}	Axial-compressive load applied to panels, lb
p_{46}	Static pressure on rigid access panel, psi (Fig. 9b)
p_c	Panel cavity pressure, psi
p_n	Local static pressure on panel surface, psf

$p_{t\infty}$	Free-stream total pressure, psf
p_∞	Free-stream static pressure, psf
q_∞	Free-stream dynamic pressure, psf
R_m	Total pressure orifices on rake, Fig. 5
Re/ft	Reynolds number per foot, U_∞/ν_∞
U_∞	Free-stream velocity, ft/sec
u	Local velocity, ft/sec
V_ℓ	Velocity outside boundary layer, ft/sec
x	Distance from forward edge of pressure panel, in. (Fig. 9a)
y	Vertical distance above panel surface, in.
z	Vertical distance above Tunnel 1T floor, in.
Δp_c	Differential pressure across test panel ($p_c - p_{46}$), psi
δ	Boundary-layer thickness to $u/V_\ell = 0.99$, in.
δ^*	Boundary-layer displacement thickness, in.
θ	Boundary-layer momentum thickness, in.
ν_∞	Free-stream kinematic viscosity, ft^2/sec
ϕ	Angular coordinate of circumferential ray of static-pressure orifices on pressure panel, deg (Fig. 9a)

CONFIGURATION NOMENCLATURE

BT_{1-3}	Boattails (Fig. 5)
h_{1-3}	Height of fixture (Fig. 5)

SECTION I INTRODUCTION

A flutter test of an array of panels from the S-IVB stage of the Saturn V vehicle was performed in the Propulsion Wind Tunnel, Transonic (16T). The purpose of this investigation was to determine the flutter characteristics of the panels at higher dynamic pressures and Mach numbers than were attainable in a previous test (Ref. 1) which was performed during a period of repair of the tunnel compressor.

The previous Saturn S-IVB Panel Flutter test in Tunnel 16T (Ref. 1) indicated a requirement for improving the flow over the floor of the tunnel diffuser, downstream of the floor-mounted fixture. Therefore a calibration-phase test was conducted on a 0.076-scale model of the fixture in the Aerodynamic Wind Tunnel, Transonic (1T) at Mach numbers from 0.80 to 1.40. The objective of this calibration phase was to determine the fixture height above the floor, and the boattail configuration which would minimize the flow separation at the entrance to the diffuser. The results of this calibration phase determined the necessary modifications for the full-scale fixture used in Tunnel 16T. To confirm the suitability of the final design of the fixture, a pressure-phase test was conducted in 16T to determine the boundary-layer characteristics and static pressure distributions on the panels at Mach numbers from 1.20 to 1.60.

SECTION II APPARATUS

2.1 WIND TUNNELS

2.1.1 Tunnel 1T

Tunnel 1T is an open-circuit, continuous flow wind tunnel capable of operating at Mach numbers from 0.5 to 1.50. The total pressure is approximately 1.4 atm throughout the operating range. The test section is 12 in. square, 37.5 in. long and has perforated walls. Details of the perforated walls and the location of the calibration model in the test section are shown in Fig. 1 (Appendix I). Photographs of three different configurations of the calibration models installed are presented in Fig. 2. Tunnel 1T is described further in Ref. 2.

2.1.2 Tunnel 16T

Tunnel 16T is a variable density wind tunnel capable of operating at Mach numbers between 0.55 and 1.60. The tunnel is equipped with a plenum evacuation system, and the test section is formed by fixed parallel top and bottom perforated walls and perforated variable angle sidewalls. A more complete description of the wind tunnel and its operating characteristics is given in Ref. 2.

The location of the floor-mounted model and details of the perforated walls are shown in Fig. 3. A photograph of the flutter model installed in the test section is presented in Fig. 4.

2.2 TEST ARTICLES

2.2.1 Calibration Models, Tunnel 1T

An existing 0.076-scale model of the Saturn S-IVB panel fixture was modified to incorporate three different sets of side support struts (h_1 , h_2 , and h_3) and three different boattail configurations (BT₁, BT₂, and BT₃) as shown in Figs. 5a and b. Figure 6 shows the wake rake that was mounted on the aerodynamic tip of the simulated scavenging scoop. The leading edges of the tubes were at tunnel station 37.3 in.

2.2.2 Pressure Panel, Tunnel 16T

The same basic mounting fixture was used for both the pressure and flutter panels in Tunnel 16T (Fig. 7). The boundary-layer rake shown in Fig. 8 was placed at three different positions on the rigid panel during the pressure phase. This mounting fixture was composed of four basic sections: the leading-edge ramp, the two side-support struts, the center section, and the boattail fairing. The rigid pressure panel was mounted to a different center section from the one used to support the flutter panel. Both of these center sections were constructed as pressure vessels, but only the one used to support the flutter panel was sealed. A boundary-layer trip which consisted of a 1/4-in. -diam tube was installed on the leading-edge ramp as shown in Fig. 7.

Details of the rigid pressure panel which was constructed from 0.125-in. 4130 steel with three rows of static orifices equidistant from the external stiffeners are shown in Fig. 9a.

2.2.3 Flutter Panel, Tunnel 16T

Details of the flutter panel, which was new but identical in design to the previous one (Ref. 1), are presented in Fig. 9b. A 30-deg segment of the forward portion of the S-IVB stage was modified to incorporate a steel bulkhead at each end. Eight remotely controlled hydraulic jacks were placed at each end of the array of panels and connected to the steel bulkheads to apply the axial-compressive loads. Four additional jacks were placed on either side of the array to reduce the shear stress in the side panel's as axial load was applied. The end jacks were manifolded together in groups of four and in turn to a central manifold on the marginator which allowed equal pressure in all jacks. The amount of axial-compressive load applied to the array was varied from 0 to 60,000 lb.

A sponge rubber seal was placed along the bottom of each of the two end bulkheads and along the side frames to maintain a pressure seal around the array of flexible panels. An automatic regulator valve with a feedback control system was connected to a 0.5-in.-diam nitrogen supply line in order to maintain a desired pressure differential across the flutter panels.

The array of panels was divided into five bays with seven panels per bay as shown in Fig. 9b. All panels were constructed from 0.035-in.-thick 7076-T6 aluminum skin and were riveted to internal ring stiffeners and external hat sections for longitudinal stiffness.

Figure 10 is a photograph of the flexible array of panels showing static buckling (wind-off condition) in the first two bays for an axial-compressive load of approximately 40,000 lb.

2.3 INSTRUMENTATION

2.3.1 Calibration Phase, Tunnel 1T

Sixteen static-pressure orifices on the calibration models and seventeen total-pressure orifices from the wake rake were connected to a mercury manometer board. The manometer board was photographed at each Mach number, and the data were reduced manually to coefficient form. Two static orifices on the bottom surface of the model and three total-pressure tubes on the duct rake (Figs. 5a and b) were connected to pressure transducers which were located in the control room of Tunnel 1T. All transducer outputs were fed into analog-to-digital converters and then to a digital computer.

2.3.2 Pressure Phase, Tunnel 16T

Forty-three static-pressure orifices were uniformly distributed along three rays on the panel, and nine microphones with accelerometers were located on the panel as shown in Fig. 9a. All of the pressure orifices were connected to pressure transducers which were located in the tunnel plenum chamber.

One boundary-layer rake was used to measure the boundary-layer thickness at three locations on the pressure panel. The 26 total-pressure lines on the rake were also connected to transducers. The outputs from the transducers were introduced into the computer in the same manner as the static- and total-pressure outputs from the calibration phase.

2.3.3 Flutter Phase, Tunnel 16T

The thirty-five flexible flutter panels were instrumented with thirty-three 120-ohm strain-gage bridges, five microphones and five accelerometers as shown in Fig. 9b. Four of the microphones were mounted flush with the surface and the fifth was attached to the floor of the pressure cavity. The rigid access panel just forward of the flutter panels in Fig. 9b was instrumented with a static-pressure orifice, an accelerometer, and a microphone.

The signals from the strain gages, microphones, and accelerometers were amplified and fed into two magnetic tape recorders and an oscillograph with a quick processing magazine. The information obtained from the tape recorders and oscillograph consisted of panel frequencies, noise levels in the boundary-layer and pressure cavity, and acceleration levels on the structure in the vicinity of the microphones.

A transducer was connected between p₄₆ orifice (Fig. 9b) on the rigid access panel and the panel cavity. The transducer output was fed into a recorder and an automatic regulator valve. This allowed continuous monitoring and control of the pressure differential across the flutter panel.

A schematic drawing of the instrumentation layout for the flutter phase is presented in Fig. 11.

SECTION III TEST PROCEDURES

3.1 CALIBRATION PHASE, TUNNEL 1T

Pressure data were obtained with the various model configurations at Mach numbers from 0.80 to 1.40 for Reynolds numbers from 4.5×10^6 to $4.9 \times 10^6 \text{ ft}^{-1}$ (Fig. 12).

3.2 PRESSURE PHASE, TUNNEL 16T

Static-pressure distributions and boundary-layer profiles were obtained at Mach numbers from 1.20 to 1.60 for Reynolds numbers of approximately 2.4×10^6 to $4.5 \times 10^6/\text{ft}$. Data were obtained with the boundary-layer rake mounted in the forward, center, and aft positions on the pressure panel.

3.3 FLUTTER PHASE, TUNNEL 16T

The Mach numbers 1.30, 1.40, 1.50, and 1.60 were established at low dynamic pressures. The dynamic pressure was slowly increased in steps at constant Mach number until either the maximum value or a designated limit was reached. The pressure differential (Δp_c) across the panels was maintained at 0.5 psi as the tunnel conditions were being changed. At each increment in dynamic pressure the tunnel conditions were held constant and the array of panels was axially loaded in compression from 0 to 60,000 lb. When flutter reached a significant amplitude the differential pressure was increased to 2.0 psi to damp it out and minimize flutter time on the panel and strain gages.

3.4 PRECISION OF MEASUREMENTS

The magnitude of the uncertainties involved in the tunnel conditions is estimated to be as follows:

	<u>1T</u>	<u>16T</u>
Mach number	± 0.003	± 0.005
Total pressure	$\pm 6 \text{ psf}$	$\pm 5 \text{ psf}$
Dynamic pressure	$\pm 0.5 \text{ percent}$	$\pm 0.5 \text{ percent}$
Total temperature	$\pm 3^\circ\text{F}$	$\pm 5^\circ\text{F}$

SECTION IV RESULTS AND DISCUSSION

4.1 CALIBRATION PHASE, TUNNEL 1T

Six configurations were tested at Mach numbers from 0.80 to 1.40. Four of the six configurations were run with both porous and solid floors below the 0.076-scale fixture model. The data presented are for porous liner plates as no significant difference was noted between the solid and porous wall data at Mach numbers from 1.10 to 1.40. The variations of pressure coefficient (C_p) with x/L_F for the upper and lower surfaces are presented in Fig. 13. The pressure coefficient data indicate a reasonably uniform distribution over that portion of the model which corresponds to the test panels of the full-scale fixture ($x/L = 0.3$ to 0.7).

Figure 14 presents the variation of the total-pressure ratio and the stream velocity as obtained from the wake rake (Fig. 6) for three different model heights with one boattail configuration. Configurations h_1 and h_2 showed total-pressure recoveries of from approximately 90 to 95 percent at $z = 1.5$ in. This was considered adequate to prevent aggravated separation at the floor of the tunnel diffuser. Configuration h_2 was selected as the optimum height primarily because of its superior structural rigidity and ease of fabrication over h_1 .

Figure 15 shows the variation of total-pressure ratio with vertical distance above the test section floor for three boattail configurations with a constant model height (h_2). Boattail configurations BT_1 and BT_3 show similar acceptable pressure recoveries as opposed to that of boattail BT_2 . Boattail configuration BT_1 was selected since configuration BT_3 would not cover the hydraulic jacks at the rear of the panel.

The full-scale fixture, which was modified according to model configuration $h_2 + BT_1$, proved successful during the Tunnel 16T test as no diffuser or compressor flow difficulties were encountered.

4.2 PRESSURE PHASE, TUNNEL 16T

Static-pressure data were obtained on the rigid pressure panel at Mach numbers from 1.20 to 1.60 for two Reynolds number levels (Fig. 16). Also boundary-layer profiles (Fig. 17) were measured at forward, center, and aft rake locations on the rigid pressure panel. A boundary-layer trip was employed to increase the thickness of the boundary-layer above the values obtained in the previous test (Ref. 1). The boundary-layer

height, displacement, and momentum thicknesses were computed from the profile data for the high Reynolds number level and are presented in Fig. 18.

The variation in pressure coefficient (C_p) with x/L at Mach numbers from 1.20 to 1.60 is presented in Fig. 19. A reasonably uniform distribution is evident up to $x/L = 0.85$. The positive increase in C_p at higher x/L values indicates the presence of a shock wave with flow separation just ahead of the external ring frame at the trailing edge of the pressure panel.

4.3 FLUTTER PHASE, TUNNEL 16T

The array of 0.035-in. aluminum panels was tested at Mach numbers from 1.30 to 1.60. Figure 20 presents the maximum dynamic pressure obtained at each Mach number for a panel differential pressure of 0.5 psi with no axial load ($P_{HT} = 0$). Flutter was not encountered on any of the panels in the array for $P_{HT} = 0$ and $\Delta p_c = 0.5$ psi.

Flutter boundaries for panels in the first three bays are presented in Fig. 21 in terms of free-stream dynamic pressure for a range of panel axial-compressive loads at $\Delta p_c = 0.5$ psi. As axial-compressive load is increased, the dynamic pressure required to initiate flutter in one or more panels in the first bay decreases at Mach numbers 1.40, 1.50, and 1.60. The test was terminated before the minimum dynamic pressure value could be obtained. However, it is reasonable to assume that this minimum point would occur at P_{HT} approximately twice the value of the wind-off static buckling load (P_{cr1}) as was noted in Refs. 1 and 3.

The effect of increasing Mach number from 1.40 to 1.60 is to reduce the axial-compressive load at which panel flutter starts in one or more panels in the first bay. Increasing the Mach number while maintaining a constant dynamic pressure and Δp_c appears to increase the zone of axial-compressive loads needed to develop panel flutter in all three bays after it has initially started in the first bay.

High speed motion pictures indicated a different mode of flutter from the previous test (Ref. 1) as panels appeared to flutter independently of adjacent panels. In all cases the amplitude of panel flutter varied directly with the applied compressive load and did not yield any structural divergence. Figure 22 presents a typical oscillograph trace showing flutter on the panels in bay one with an axial-compressive load of 42,000 lb. The strain gage numbers correspond to those of Fig. 9b.

The test was discontinued after permanent buckling was observed in three panels and two stringers in bay five as shown in Fig. 23. This is believed to have occurred at $M_\infty = 1.60$ with the panel subjected to 60,000 lb of axial load with a Δp_C of approximately zero.

SECTION V CONCLUSIONS

The following conclusions were derived from this test:

5.1 CALIBRATION PHASE

From the data presented, the intermediate height (h_2) combined with the double curvature boattail (BT_1) was selected as the optimum design for the full-scale panel fixture for the Tunnel 16T test.

5.2 PRESSURE PHASE

The pressure variations over the flutter panel were within acceptable limits.

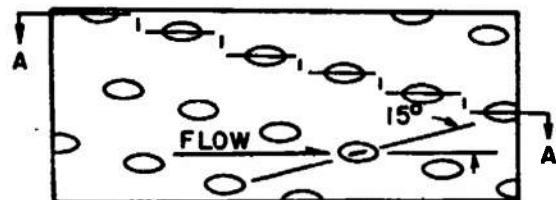
5.3 FLUTTER PHASE

1. The array of panels was flutter free for the test dynamic pressures and Mach numbers with zero axial-compressive load for a pressure differential of 0.5 psi.
2. Flutter occurred at $M_\infty = 1.40$, 1.50, and 1.60 on various panels in the first three bays when an axial load was applied in combination with a panel differential pressure of 0.5 psi.
3. The flutter mode was amplitude limited which resulted in no structural failures or fatigue cracks caused by flutter.

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**APPENDIX
ILLUSTRATIONS**



TYPICAL PERFORATED
WALL PATTERN



6% Open Area
Hole Diameter = 0.125 in.
Plate Thickness = 0.125 in.

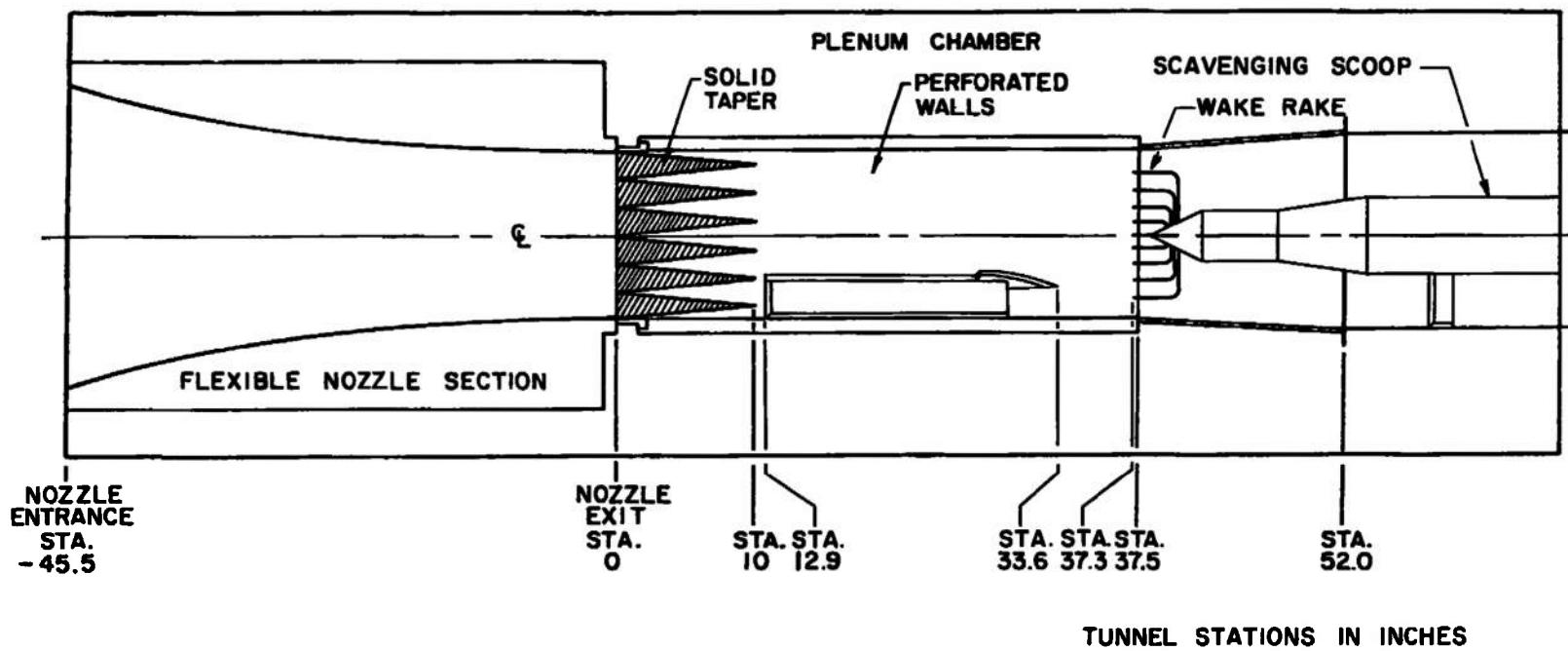
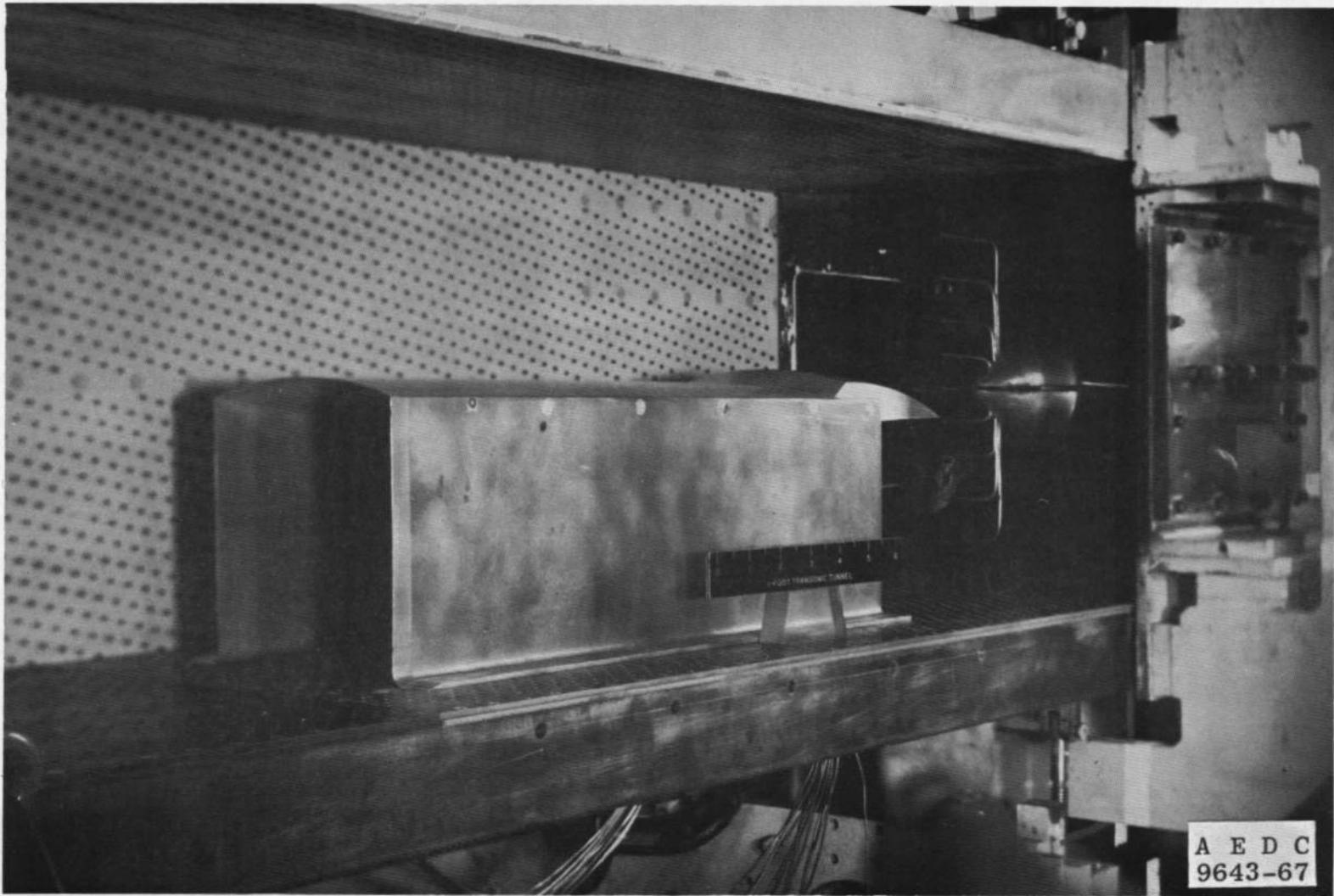
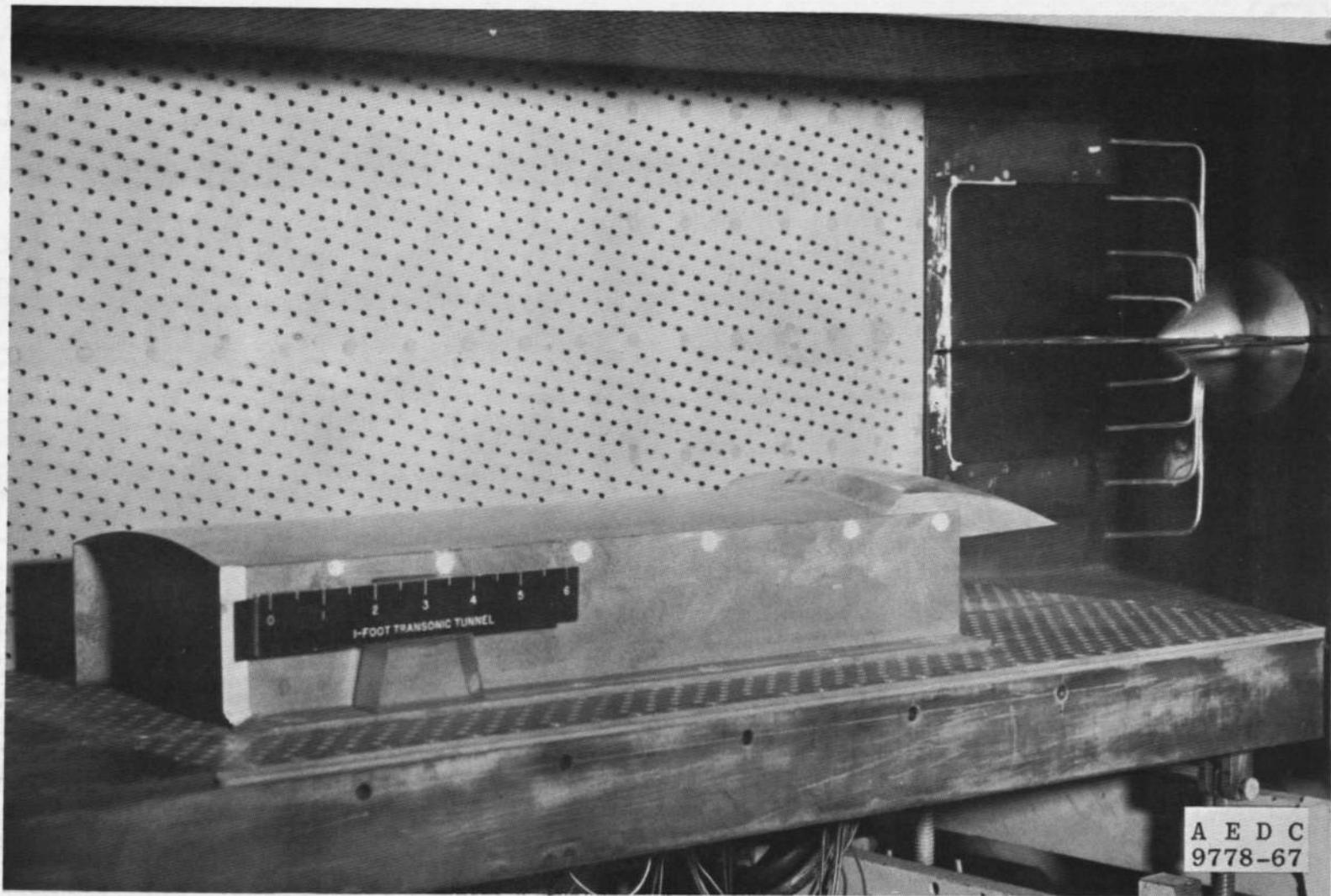


Fig. 1 Sketch of Tunnel 1T Test Section Showing Model Location



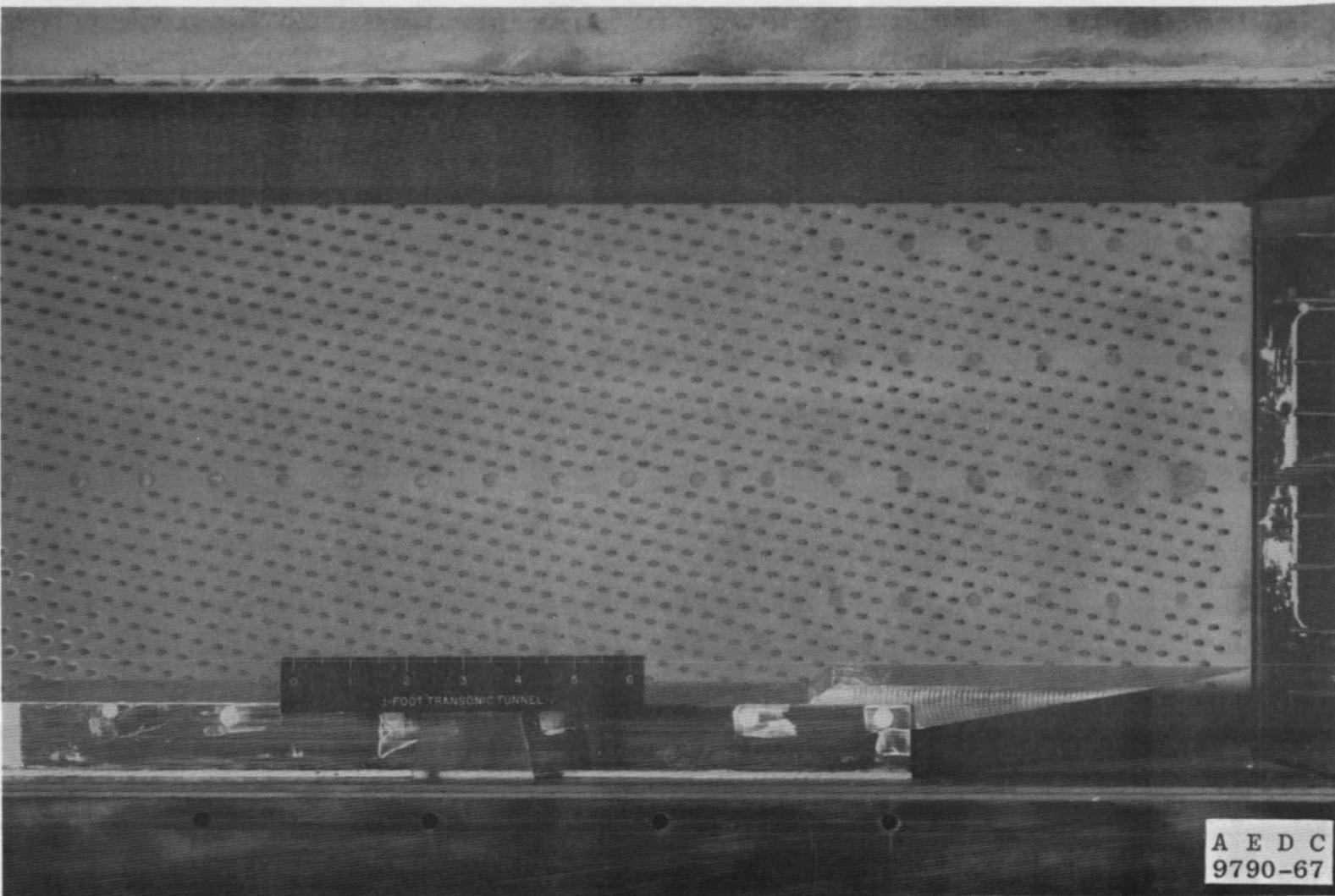
a. Configuration $h_1 + BT_1$

Fig. 2 Photograph of Calibration Models Installed in Tunnel 1T



b. Configuration $h_2 + BT_1$

Fig. 2 Continued



c. Configuration $h_3 + BT_2$
Fig. 2 Concluded

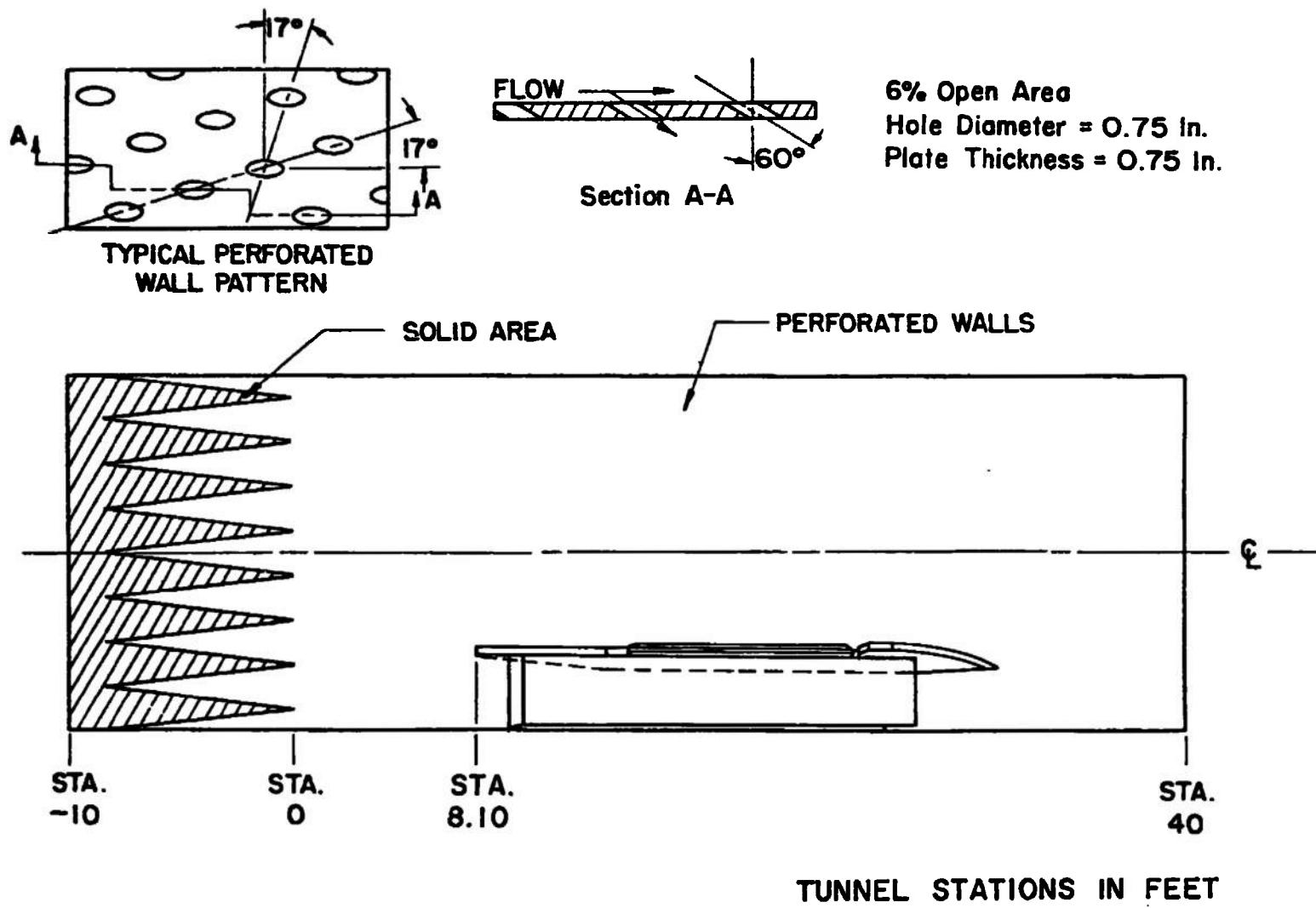


Fig. 3 Sketch of Tunnel 16T Test Section Showing Model Location

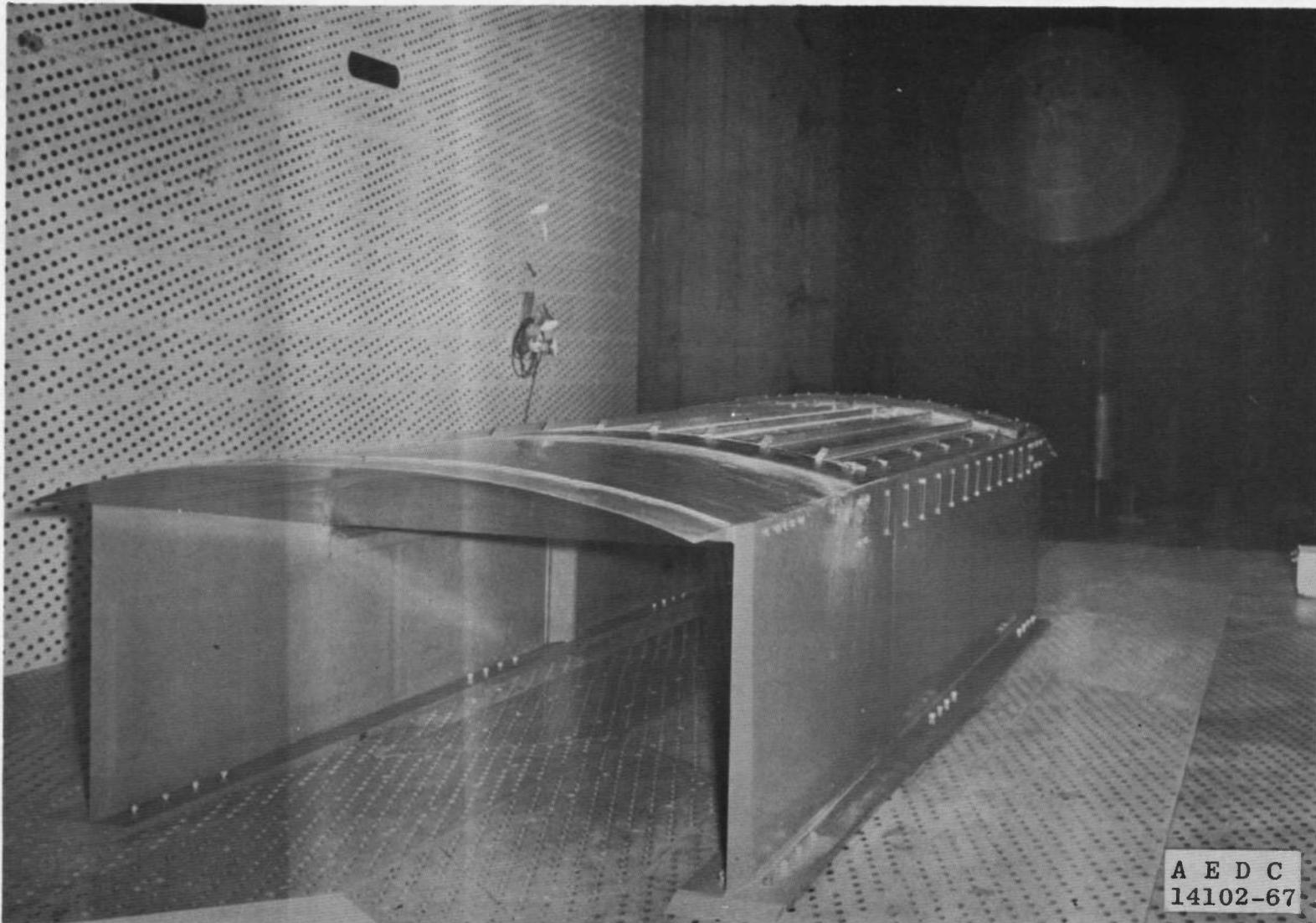
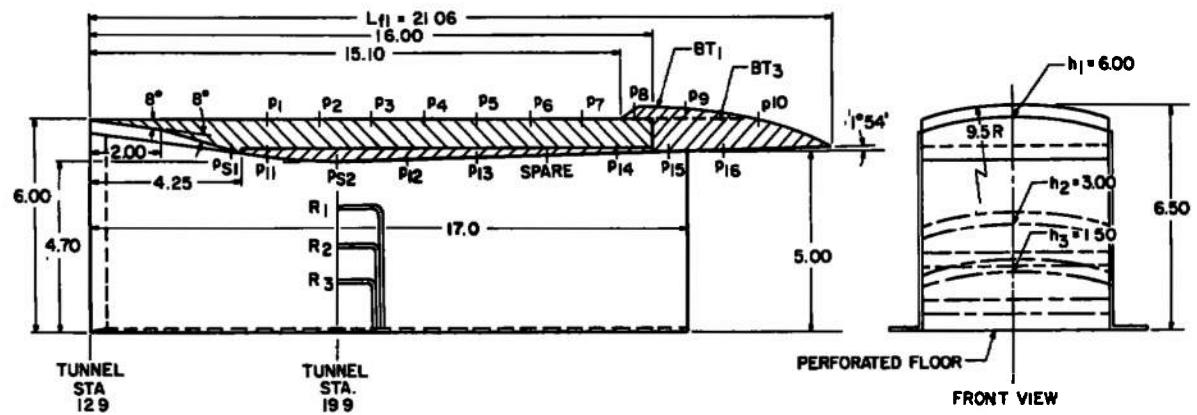
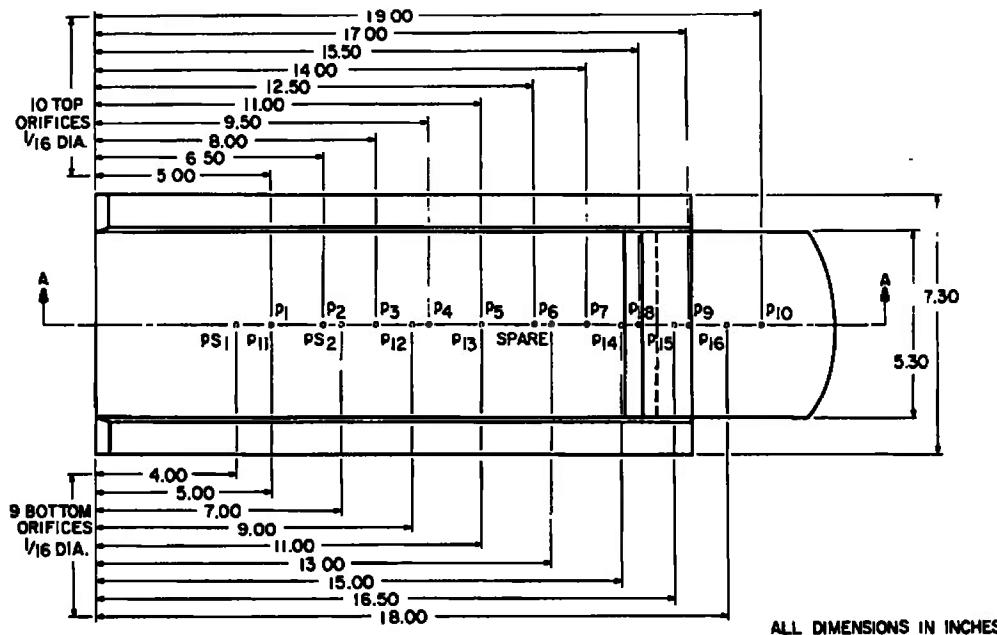
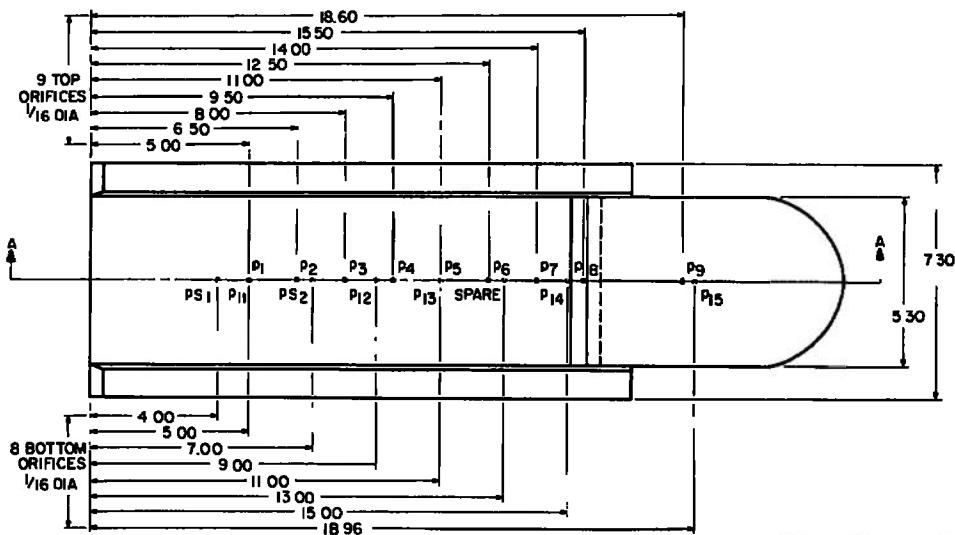


Fig. 4 Photograph of Fixture with Flutter Panel Installed in Tunnel 16T

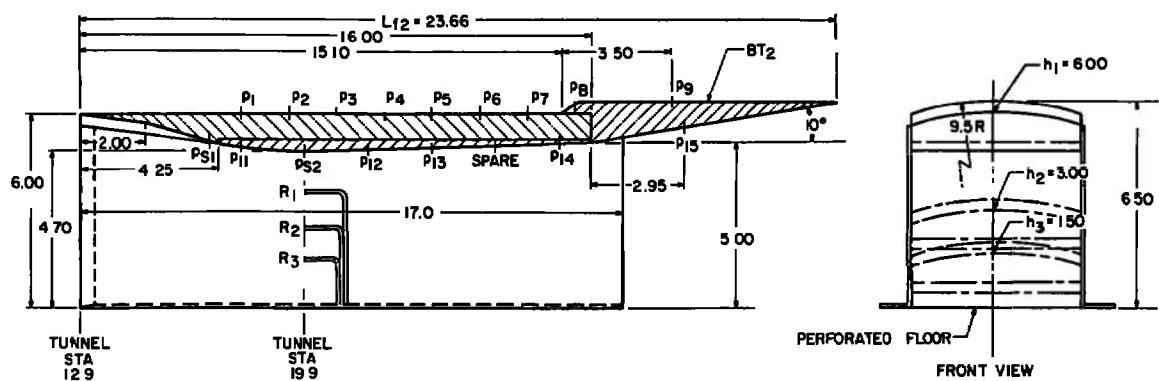


a. Configurations h_1 , h_2 , h_3 , BT₁, and BT₃

Fig. 5 Details of Calibration Models



ALL DIMENSIONS IN INCHES



SECTION A-A

b. Configurations h_1 , h_2 , h_3 , and BT_2
 Fig. 5 Concluded

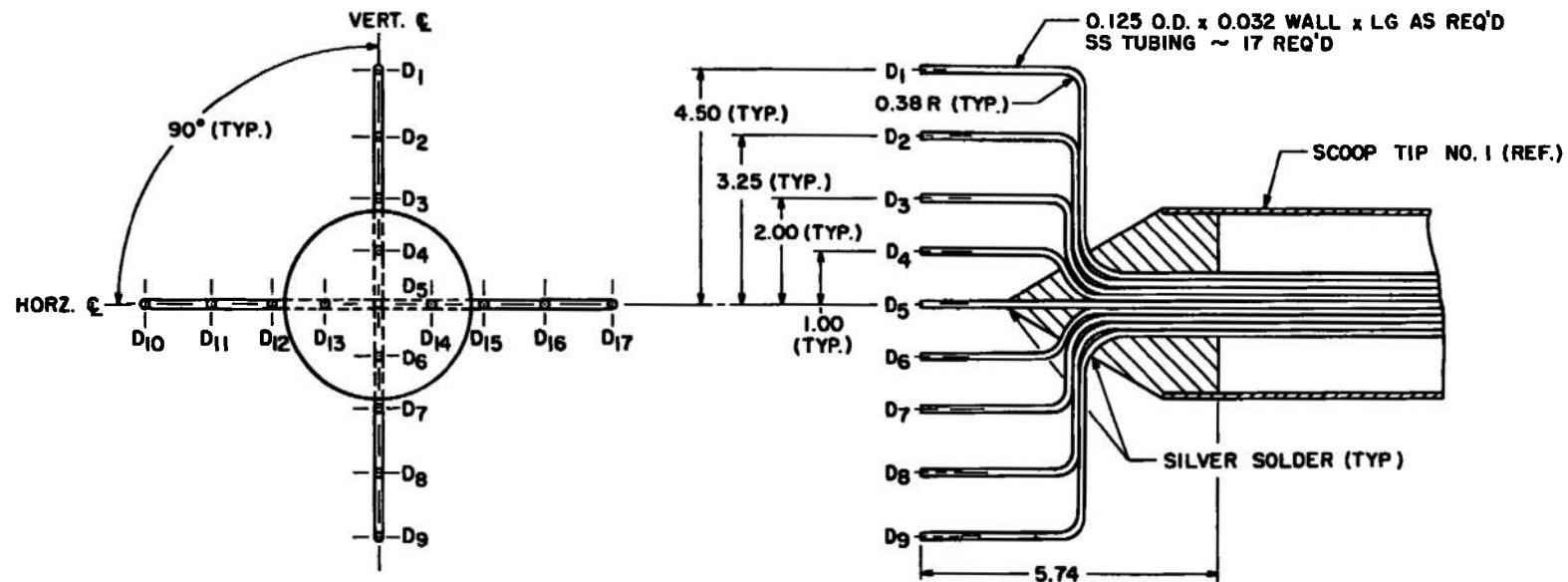


Fig. 6 Wake Rake

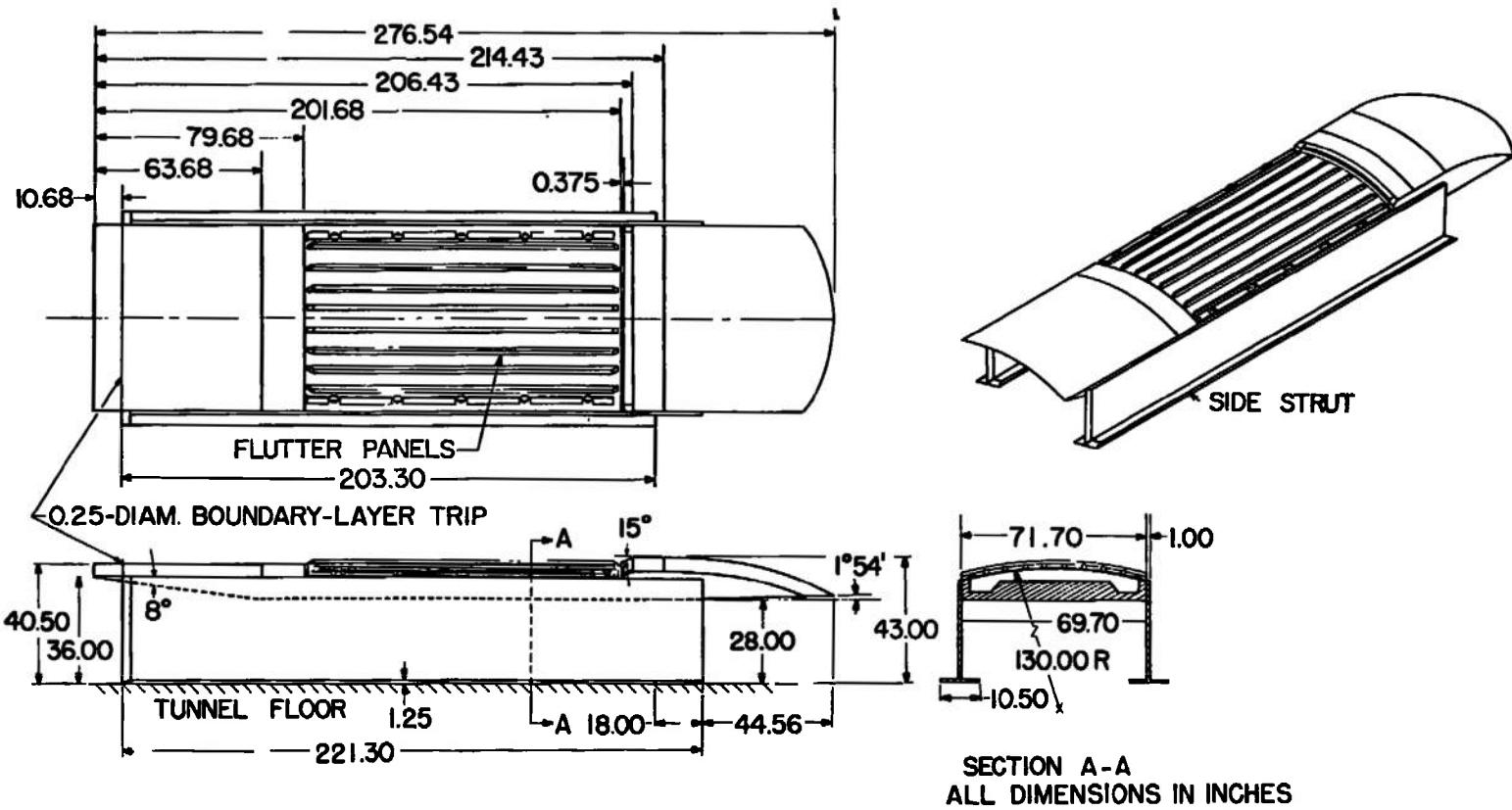


Fig. 7 Details of Test Fixture with Flutter Panel Installed

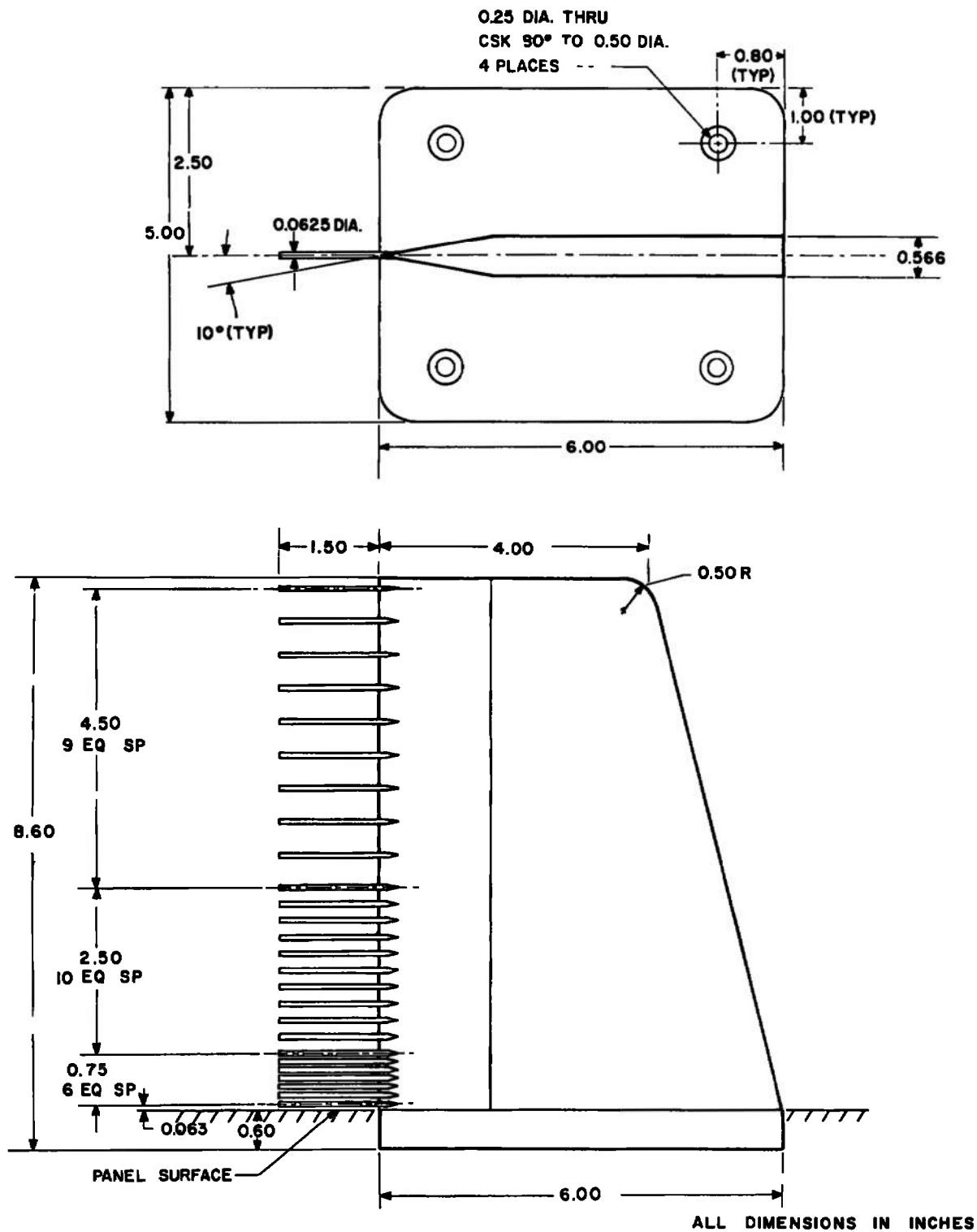
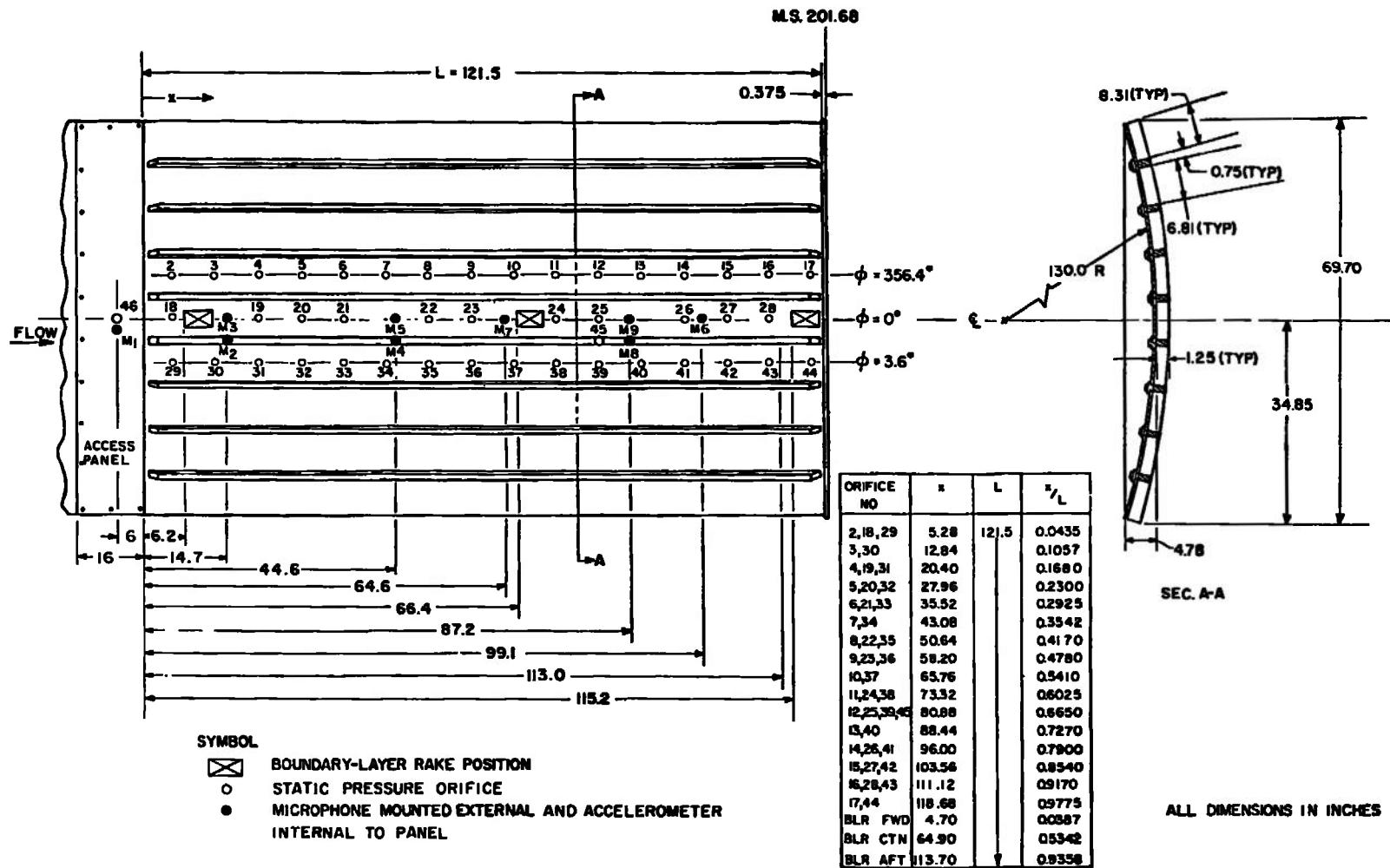
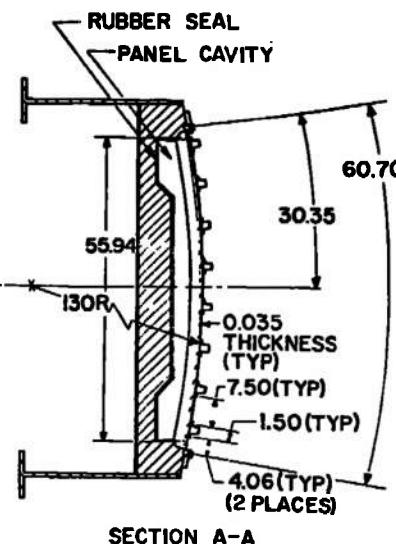
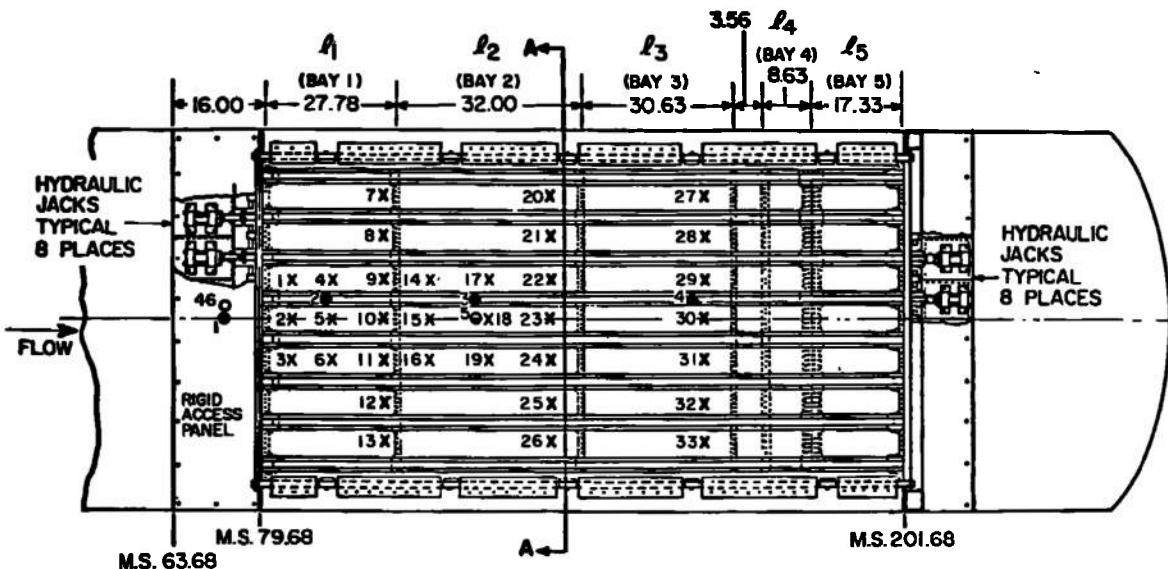


Fig. 8 Boundary-Layer Rake



a. Pressure Panel

Fig. 9 Details of Test Panels



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SYMBOL NUMBERS		LOCATION (M.S.)
STRAIN GAGES	ACCELEROMETERS AND MICROPHONES	
	1	73.68
1, 2, 3		83.62
4, 5, 6	2	90.57
7, 8, 9, 10 11, 12, 13		100.46
14, 15, 16		112.46
17, 18, 19	3, 5	120.46
20, 21, 22, 23 24, 25, 26		132.46
27, 28, 29, 30 31, 32, 33	4	163.09

- SYMBOL
- STATIC PRESSURE ORIFICE FOR P46
 - ×
 - STRAIN GAGE
 - MICROPHONE MOUNTED EXTERNALLY AND ACCELEROMETER MOUNTED INTERNALLY TO PANEL
 - MICROPHONE MOUNTED INTERNALLY TO PANEL

ALL DIMENSIONS IN INCHES

b. Flutter Panel
Fig. 9 Concluded

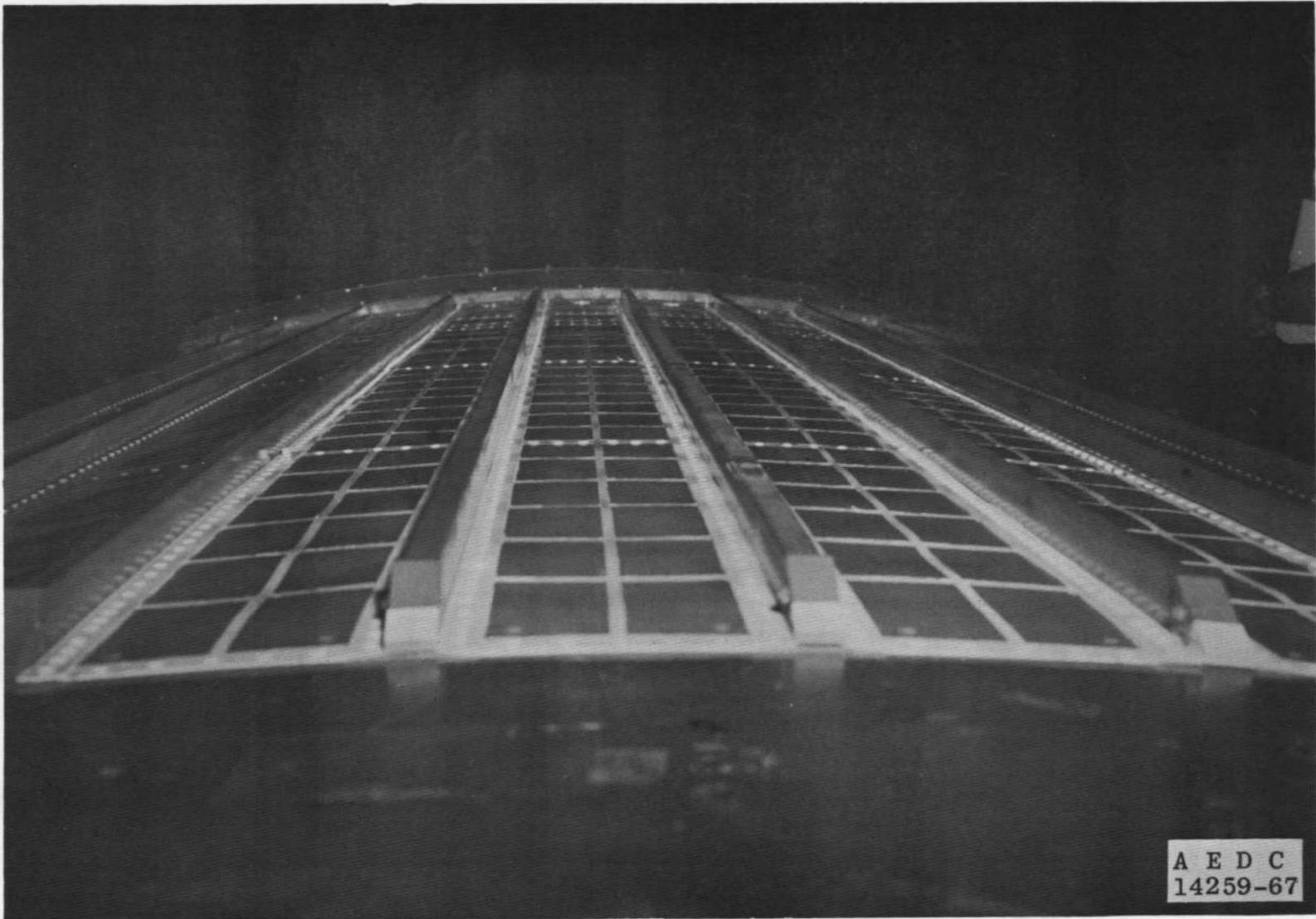


Fig. 10 Static Buckling of Flutter Panel

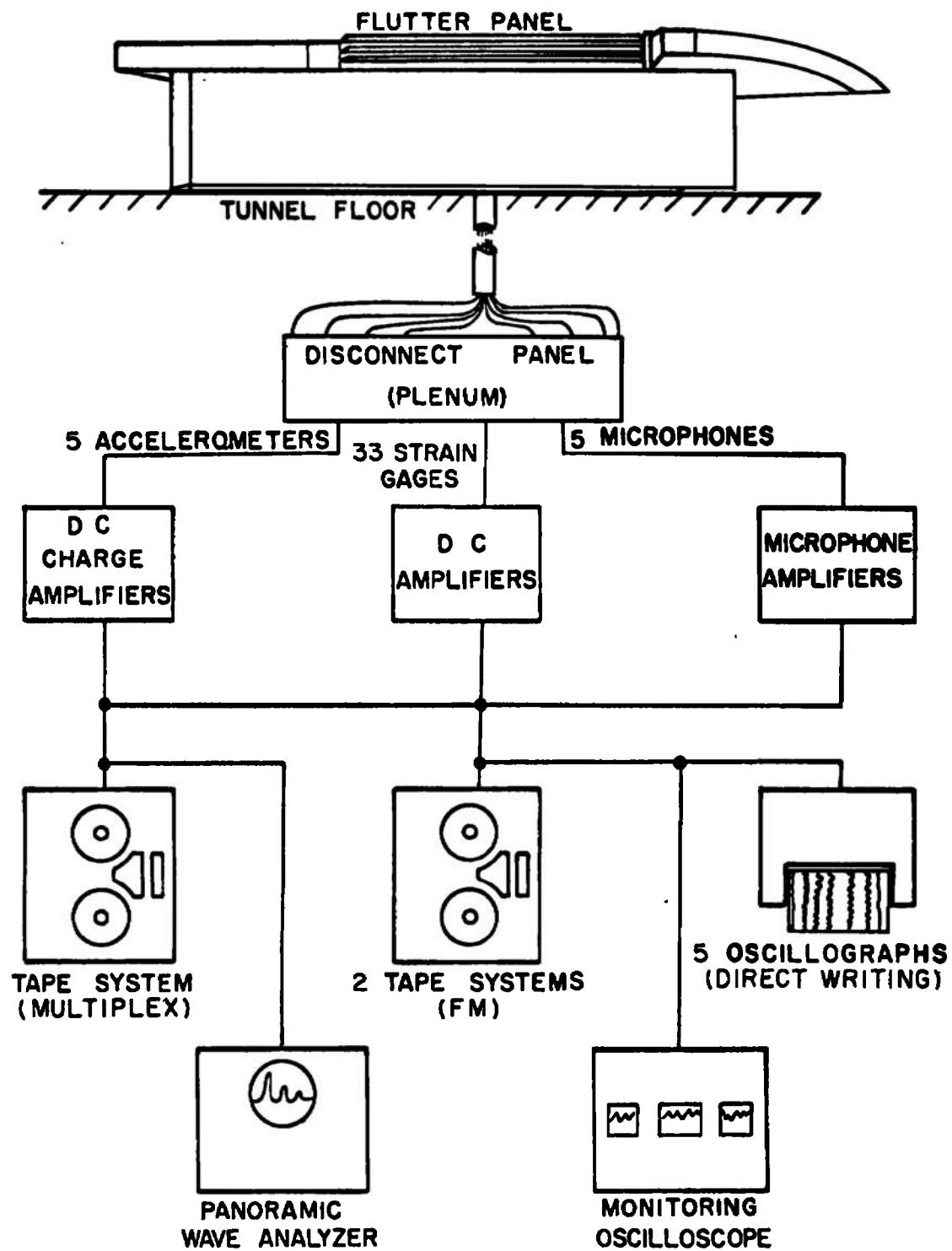


Fig. 11 Instrumentation Layout for Flutter Phase

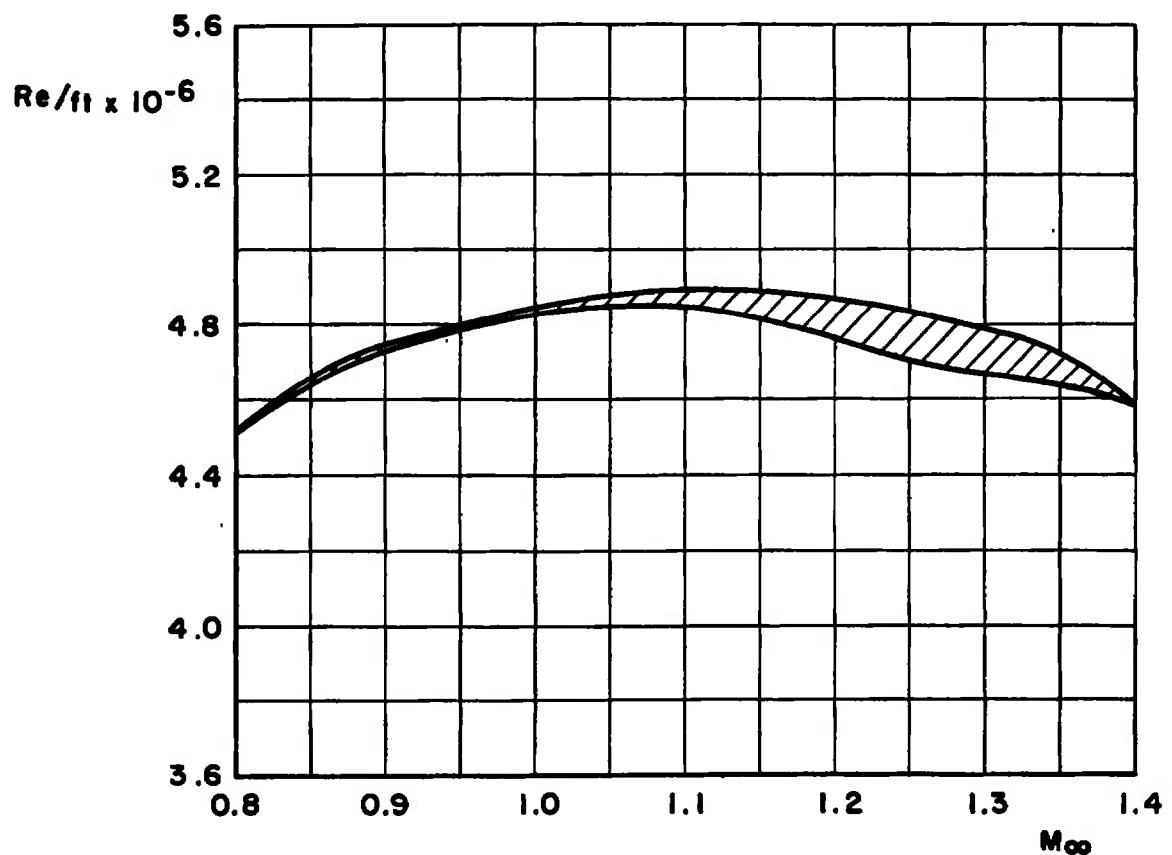


Fig. 12 Variation of Reynolds Number with Mach Number for Calibration Phase,
Tunnel 1T

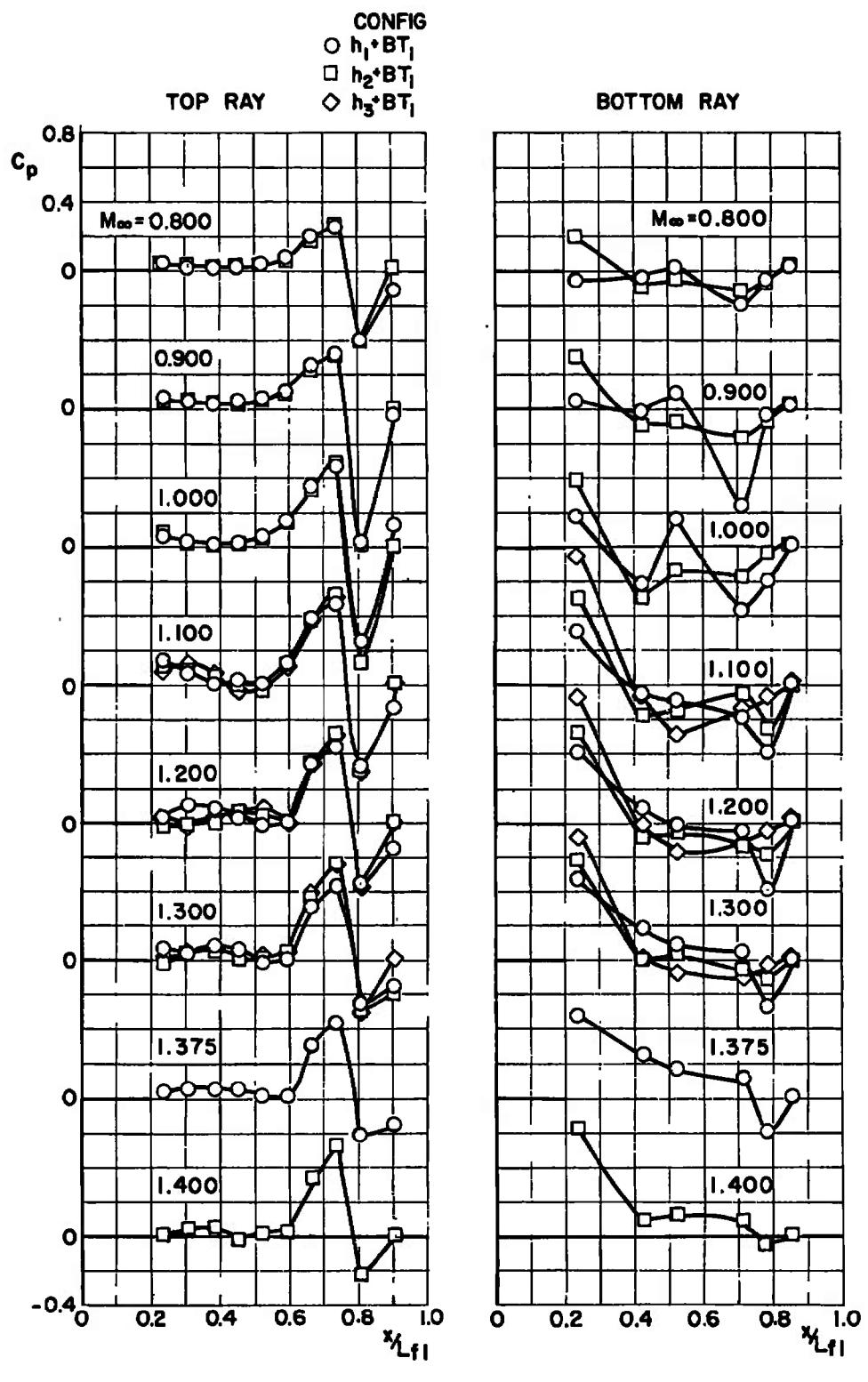


Fig. 13 Variation of Pressure Coefficient along the Calibration Model

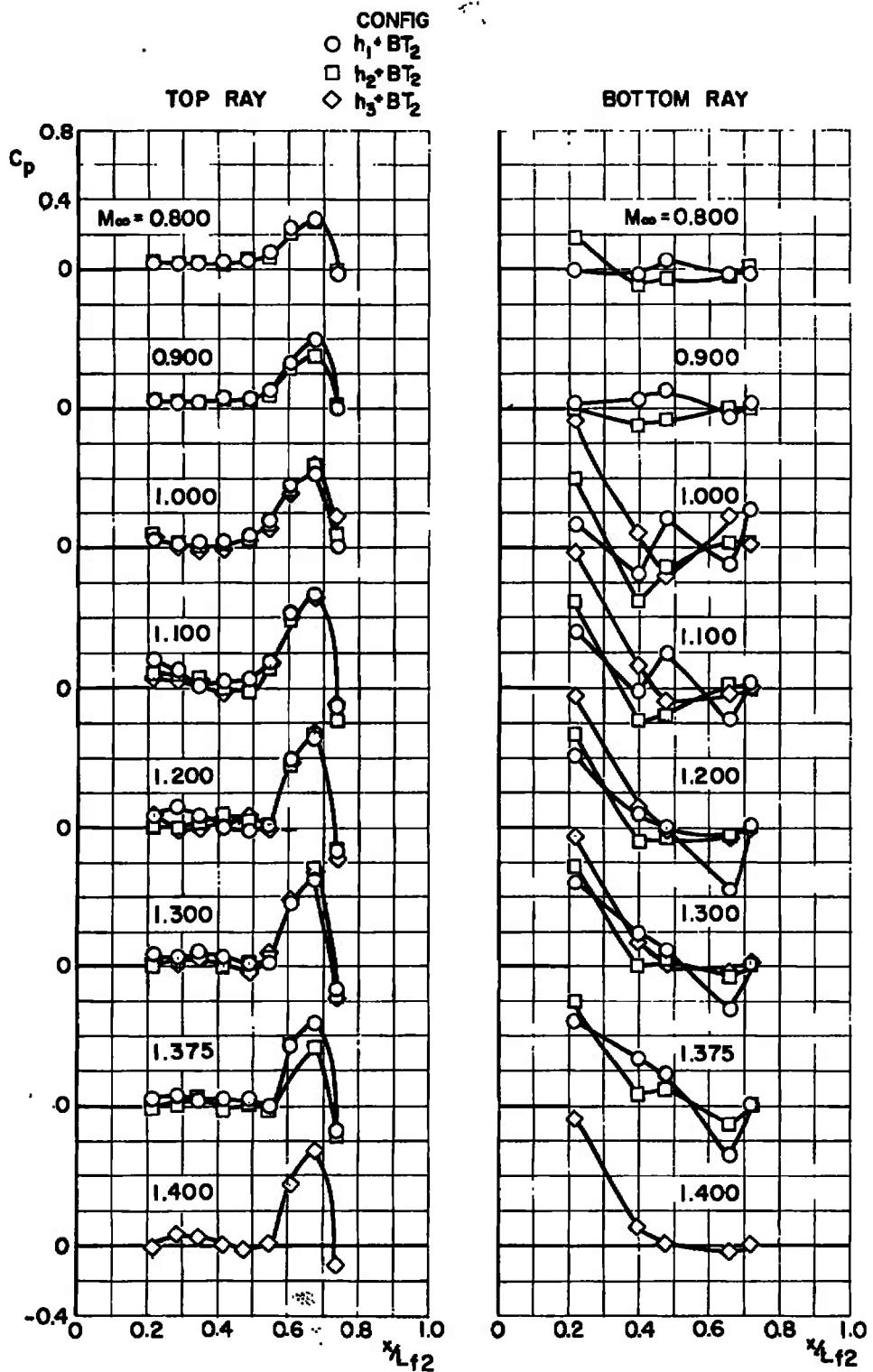
b. Boattail Configuration BT_2

Fig. 13 Concluded

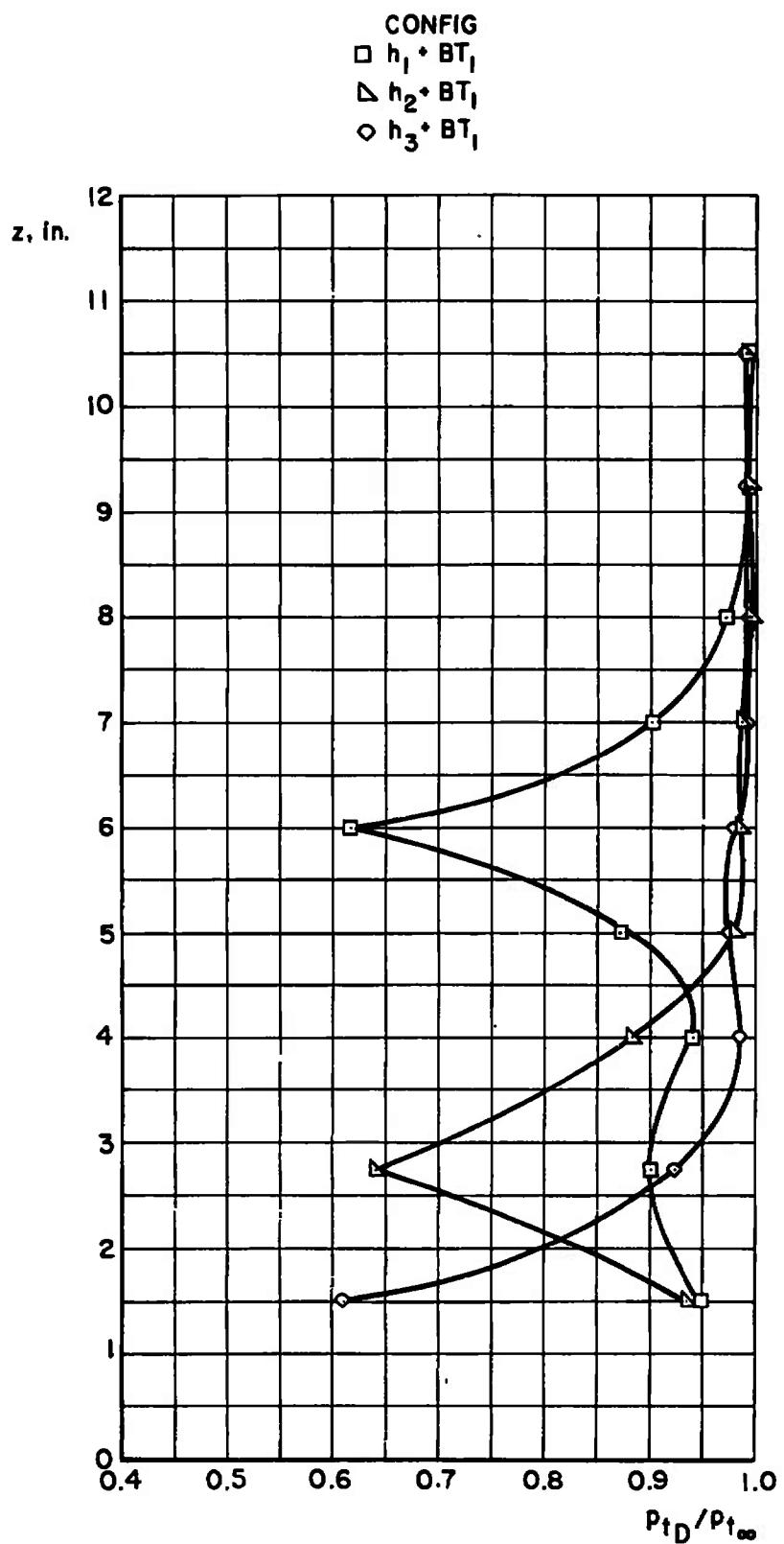
a. $M_\infty = 1.10$

Fig. 14 Variation of Total-Pressure Ratio for Various Fixture Heights

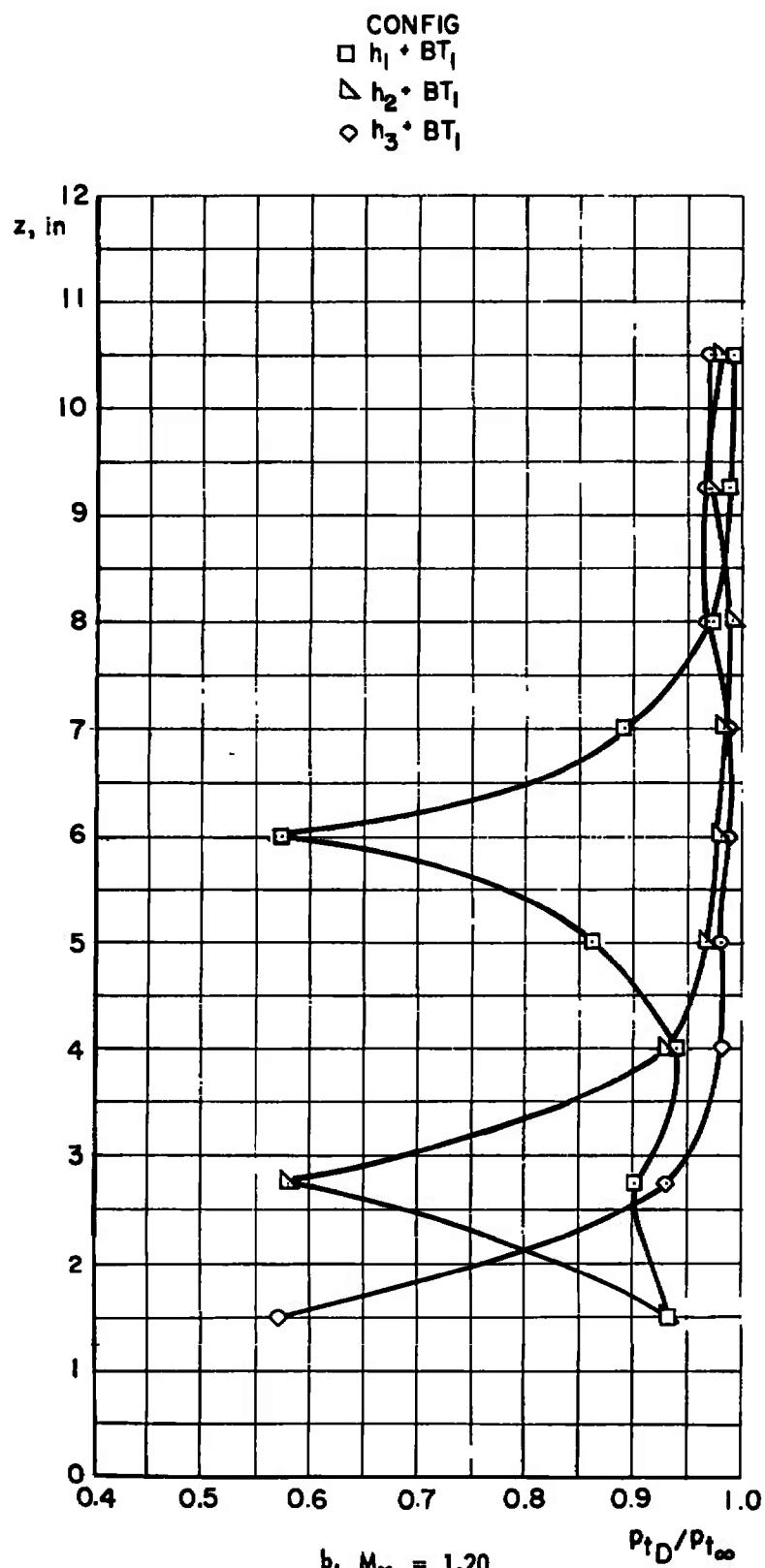


Fig. 14 Continued

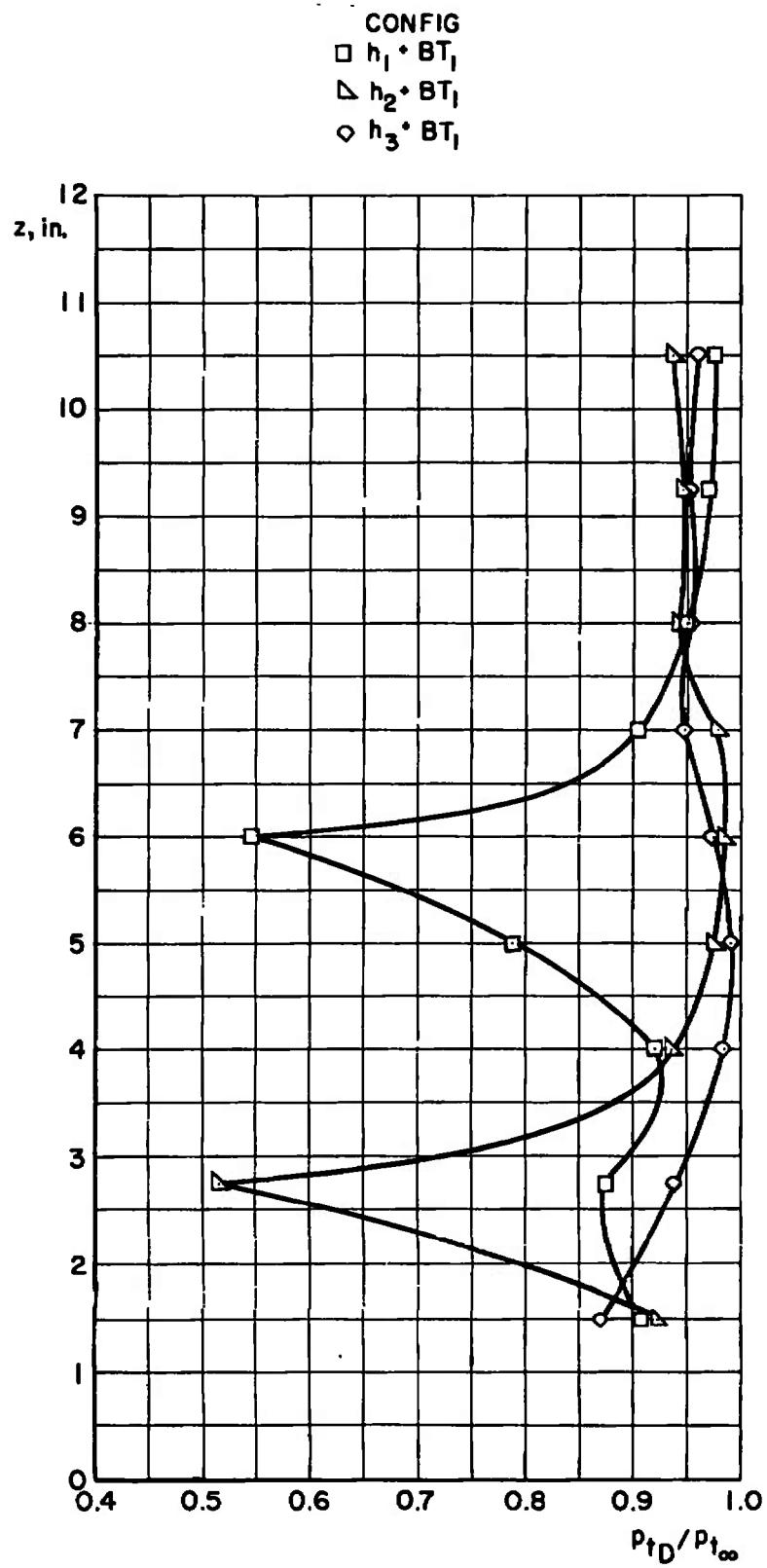
c. $M_{\infty} = 1.30$

Fig. 14 Continued

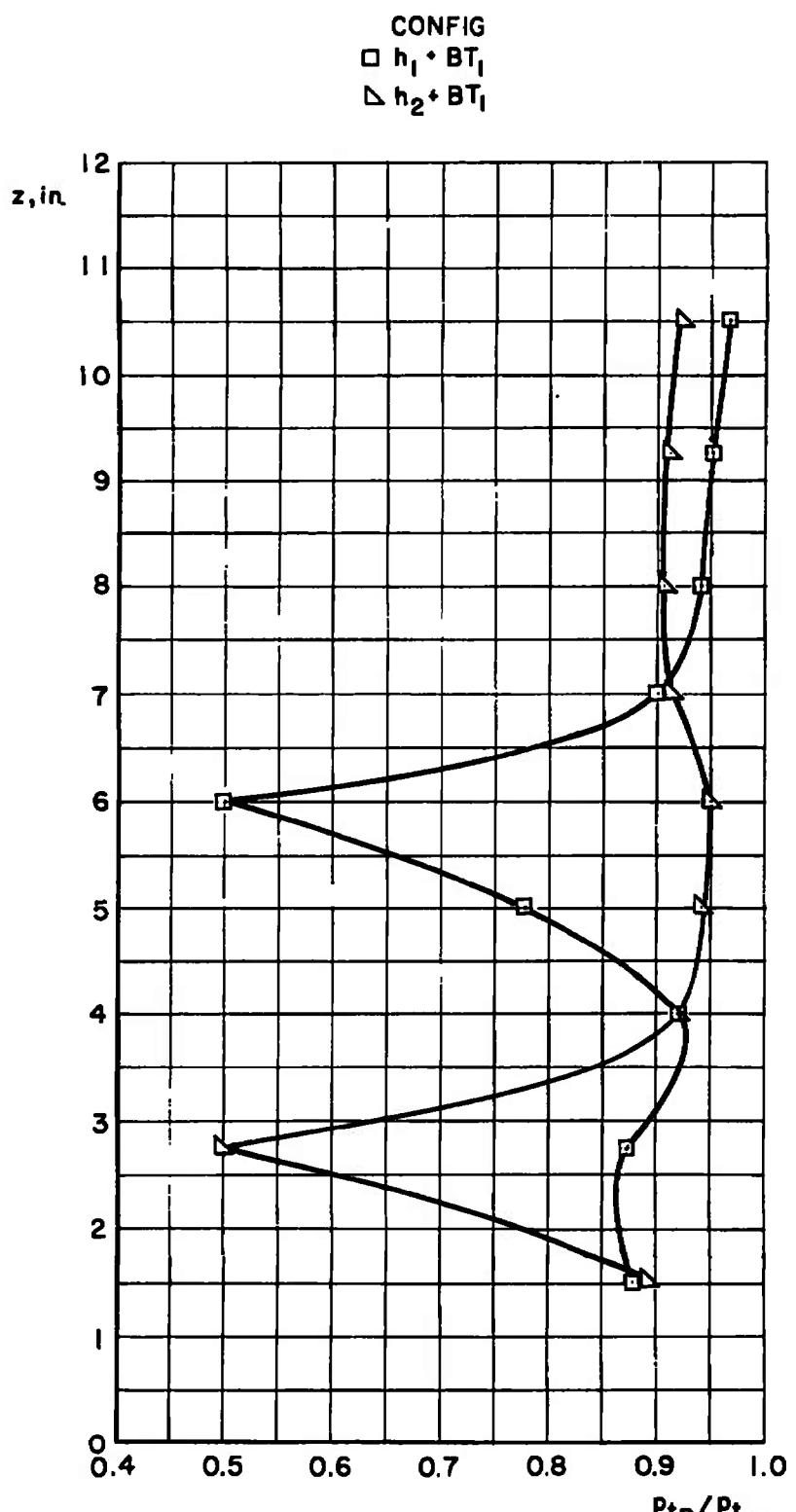


Fig. 14 Concluded

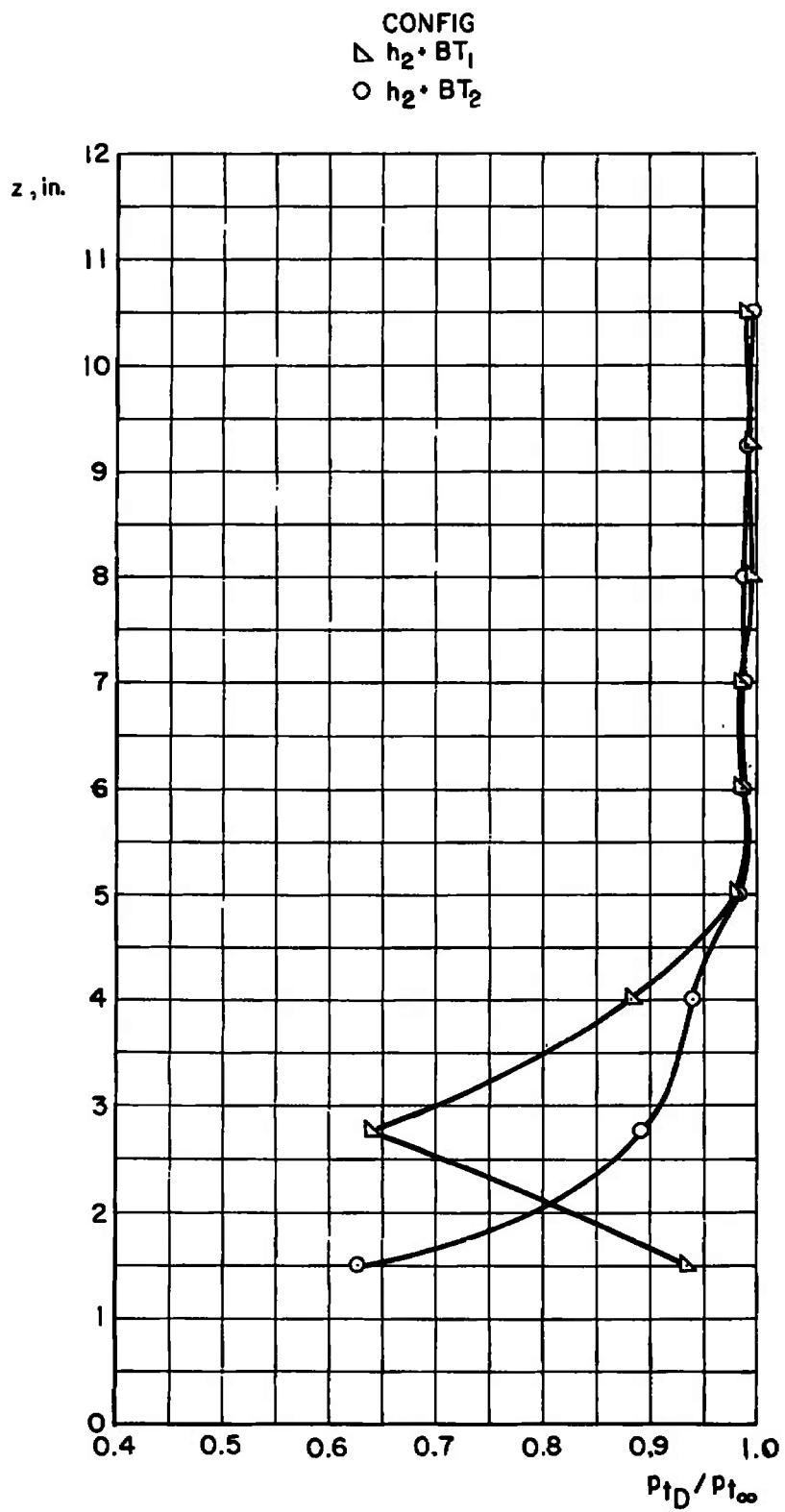


Fig. 15 Variation of Total-Pressure Ratio for Various Boattail Configurations

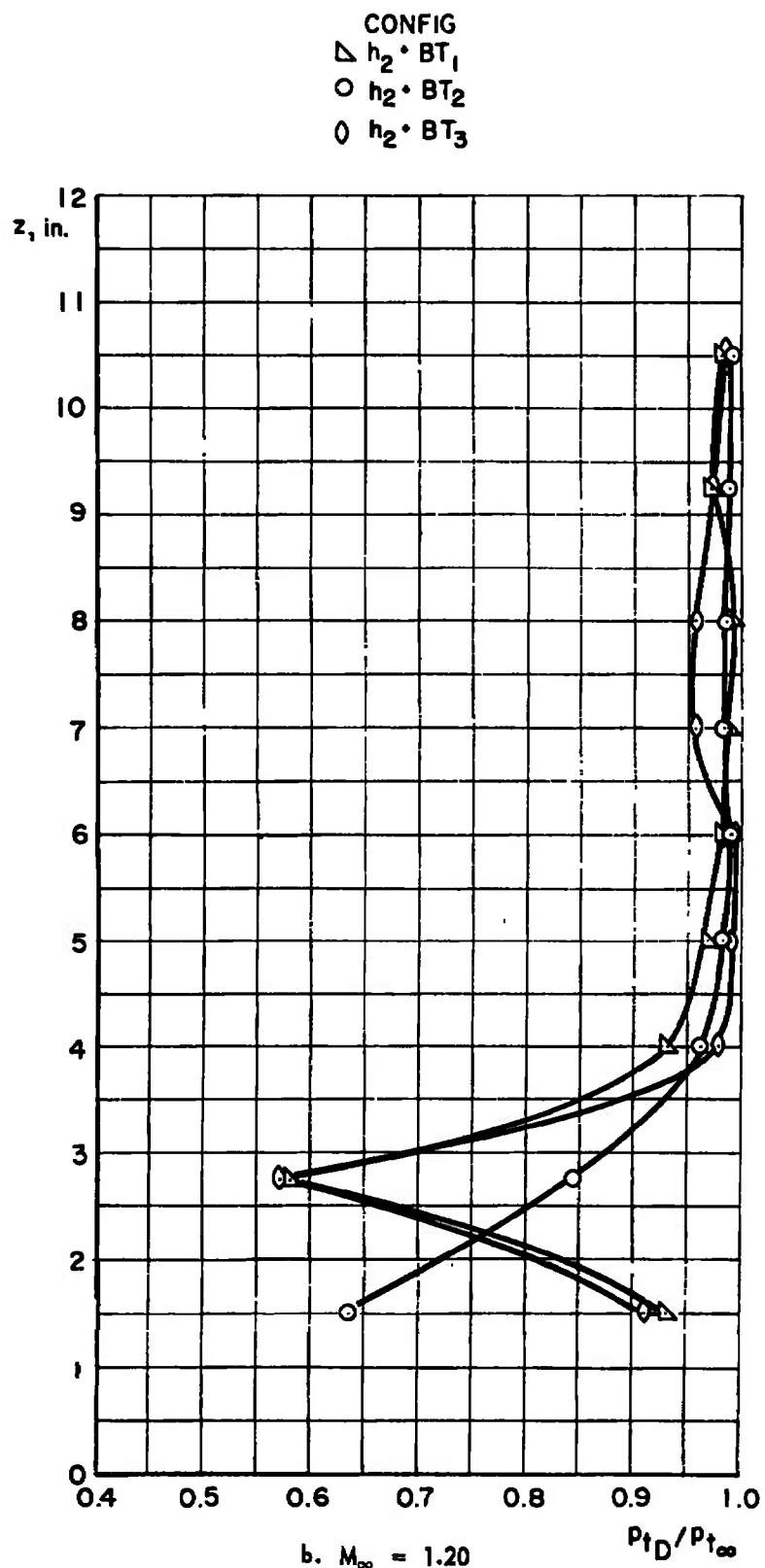


Fig. 15 Continued

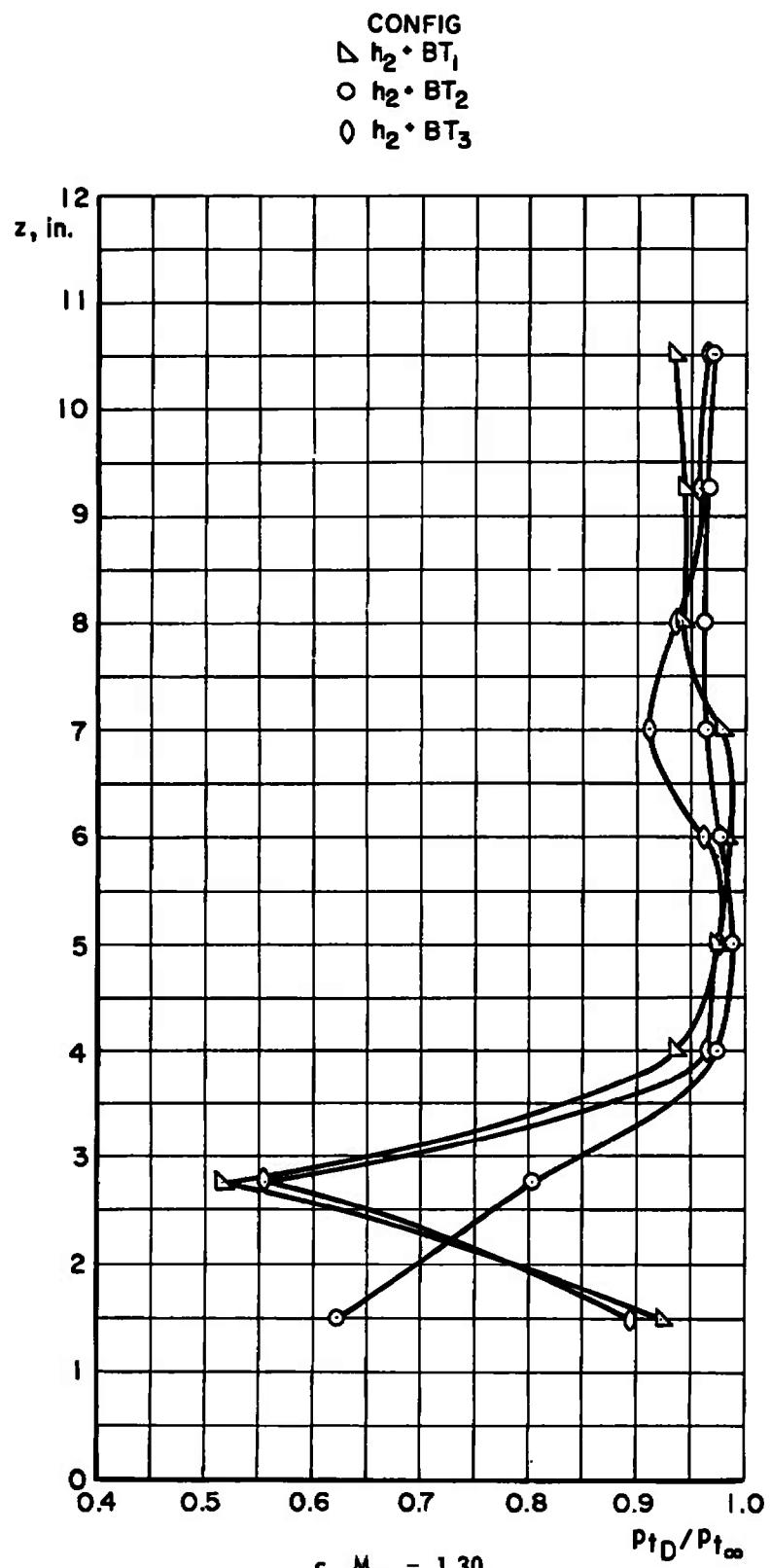


Fig. 15 Continued

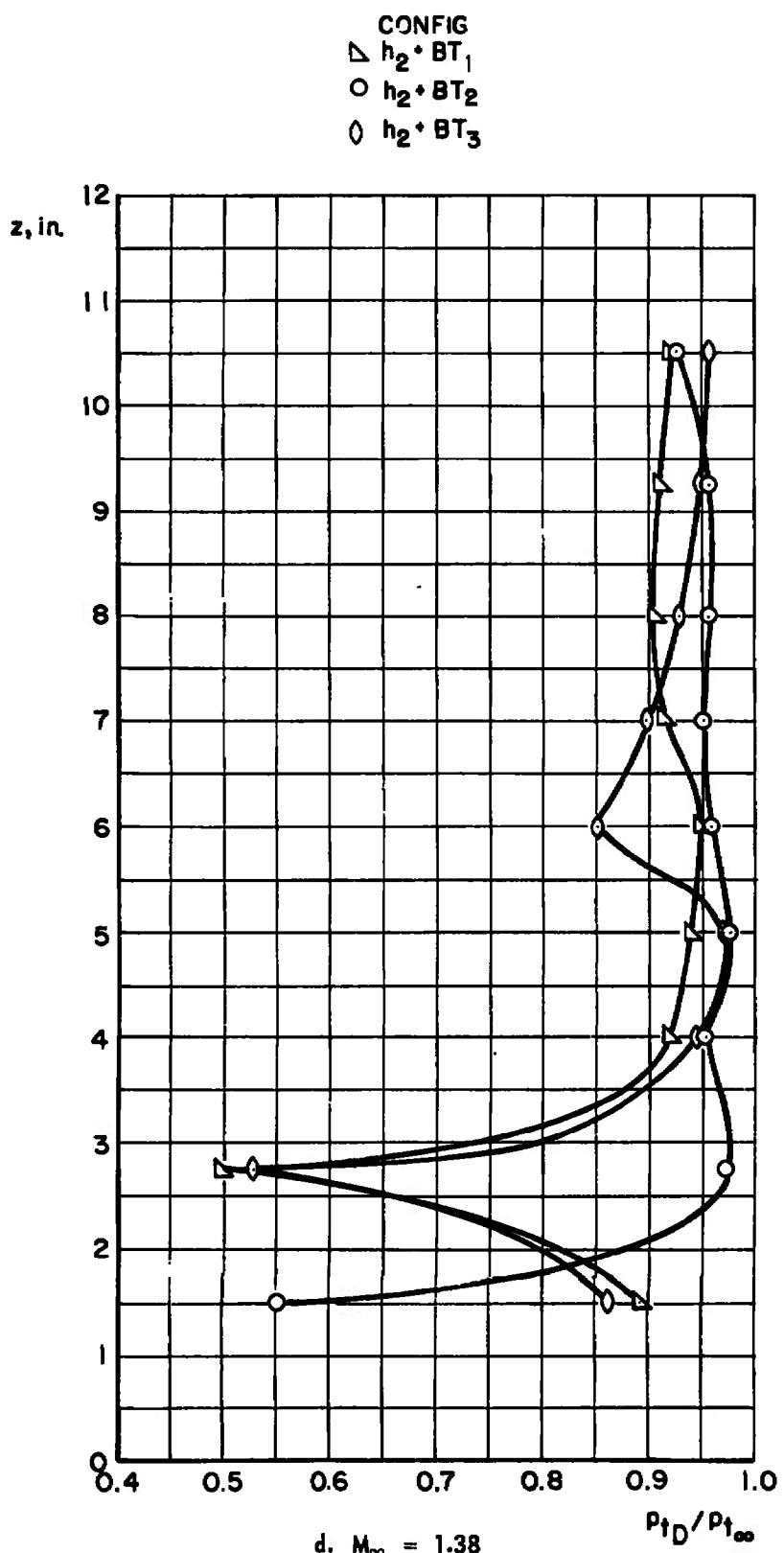


Fig. 15 Concluded

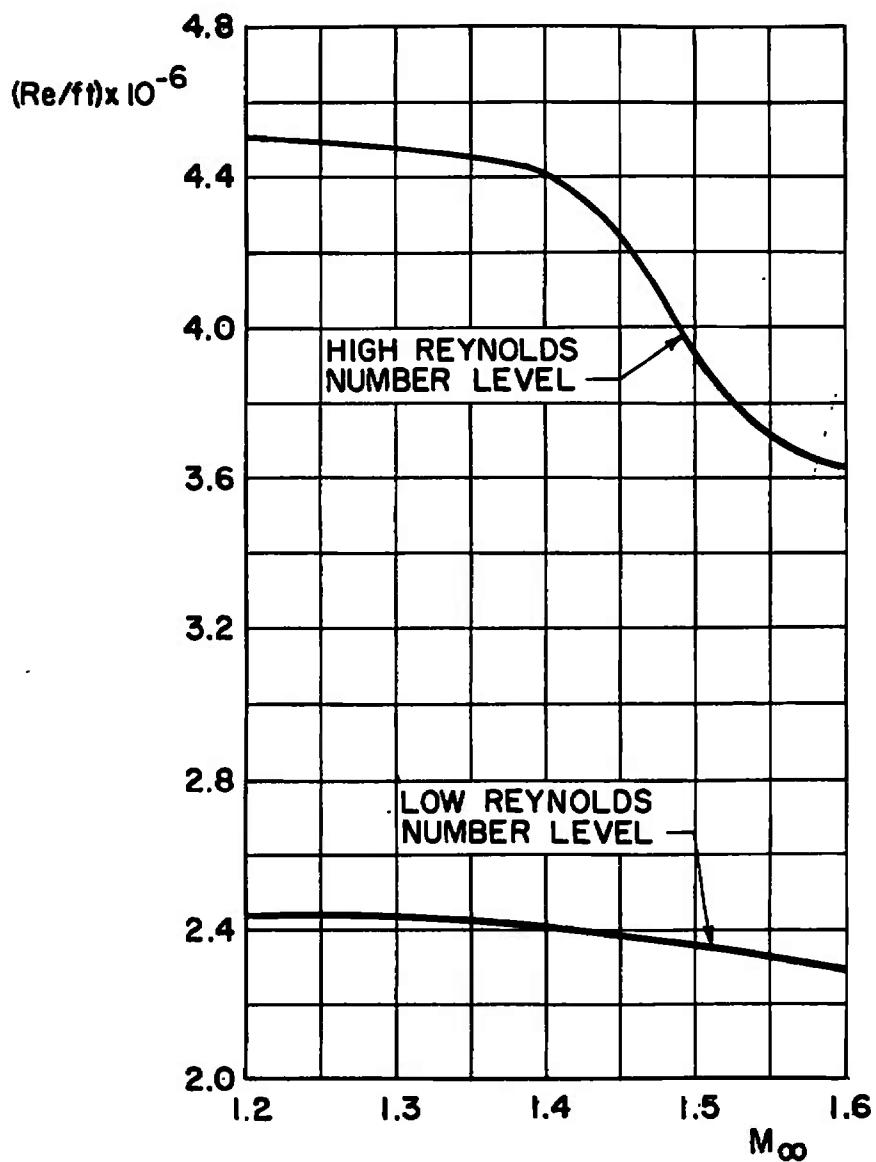


Fig. 16 Variation of Reynolds Number with Mach Number for the pressure Phase, Tunnel 16T

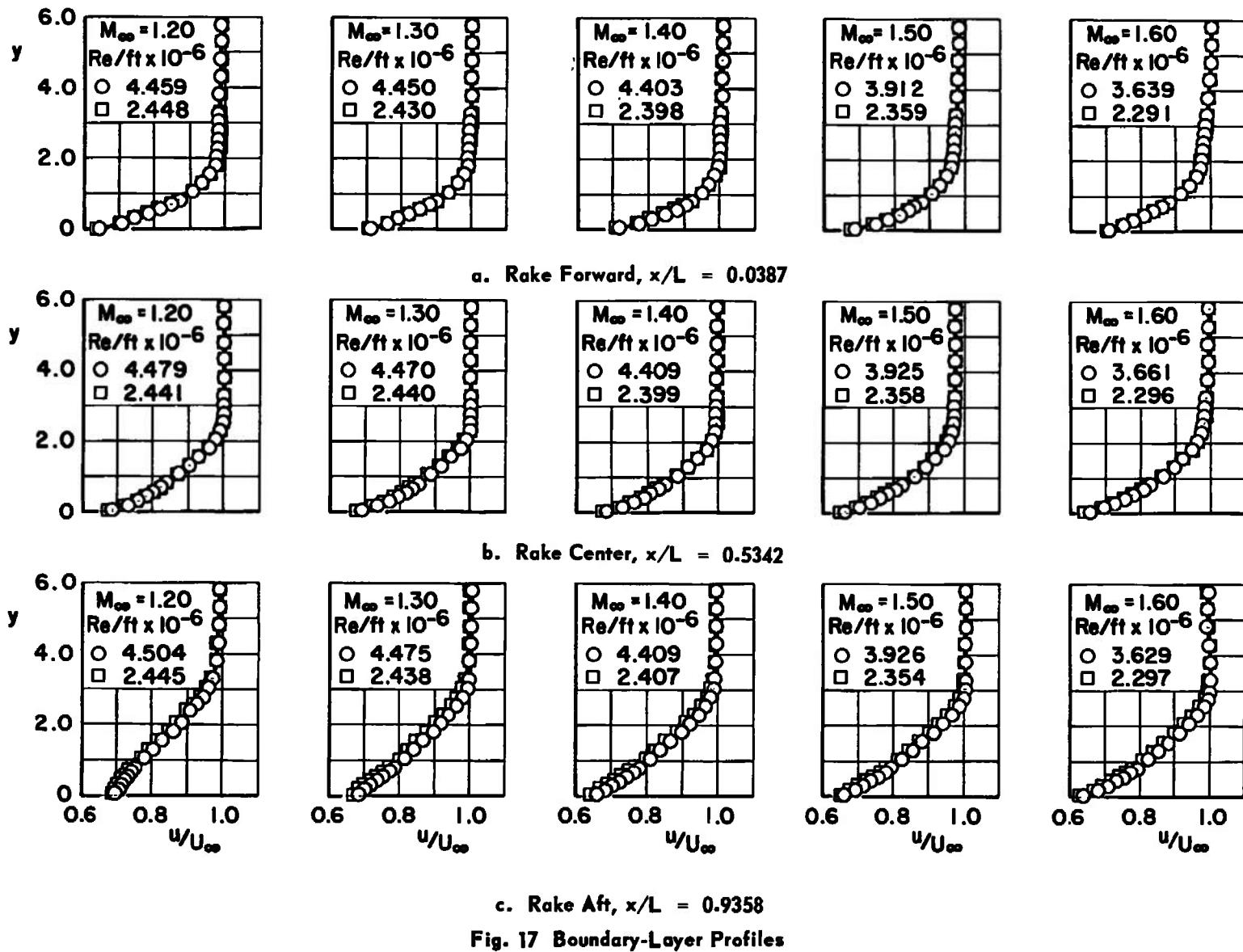


Fig. 17 Boundary-Layer Profiles

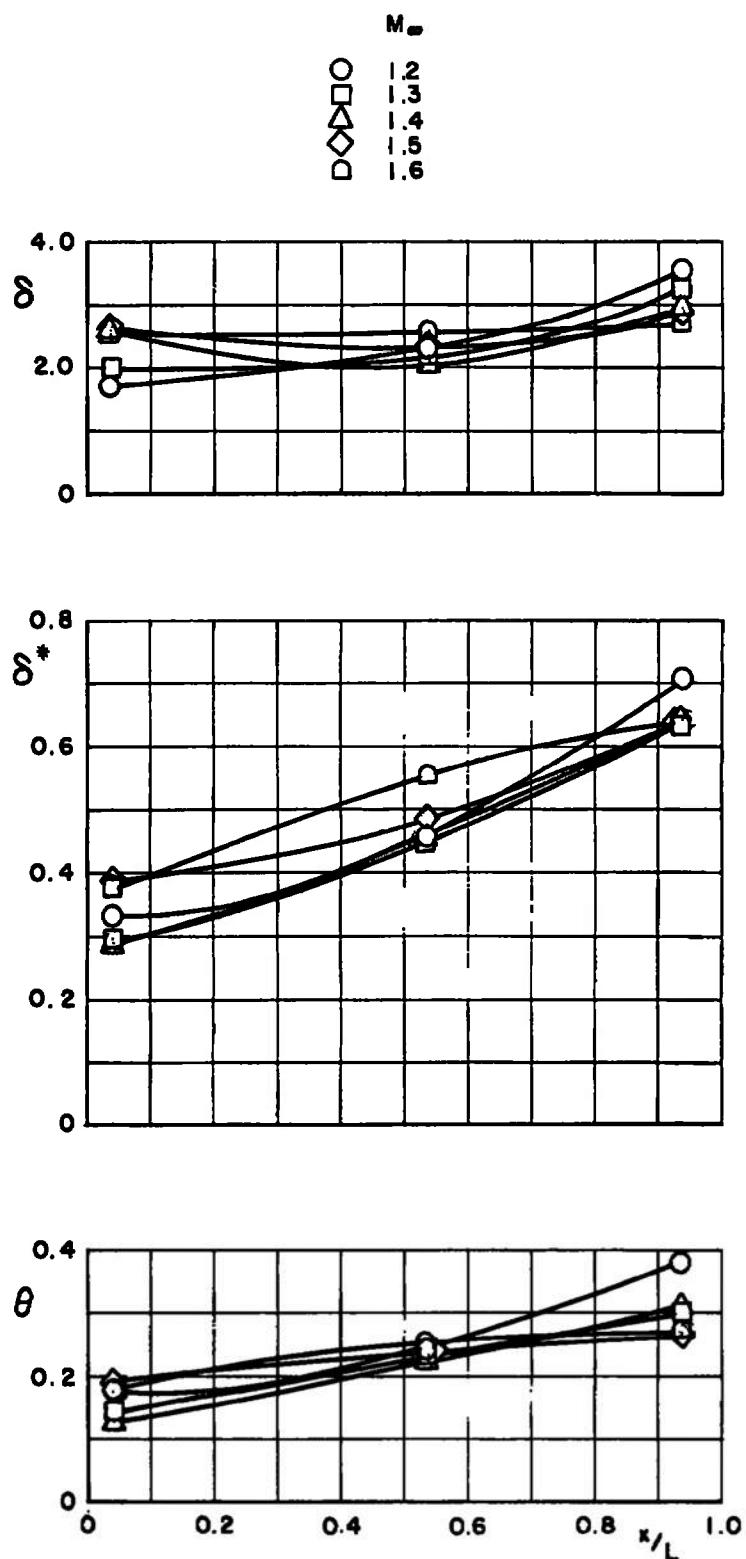


Fig. 18 Variation of Boundary-Layer Characteristics with Rake Position and Mach Number

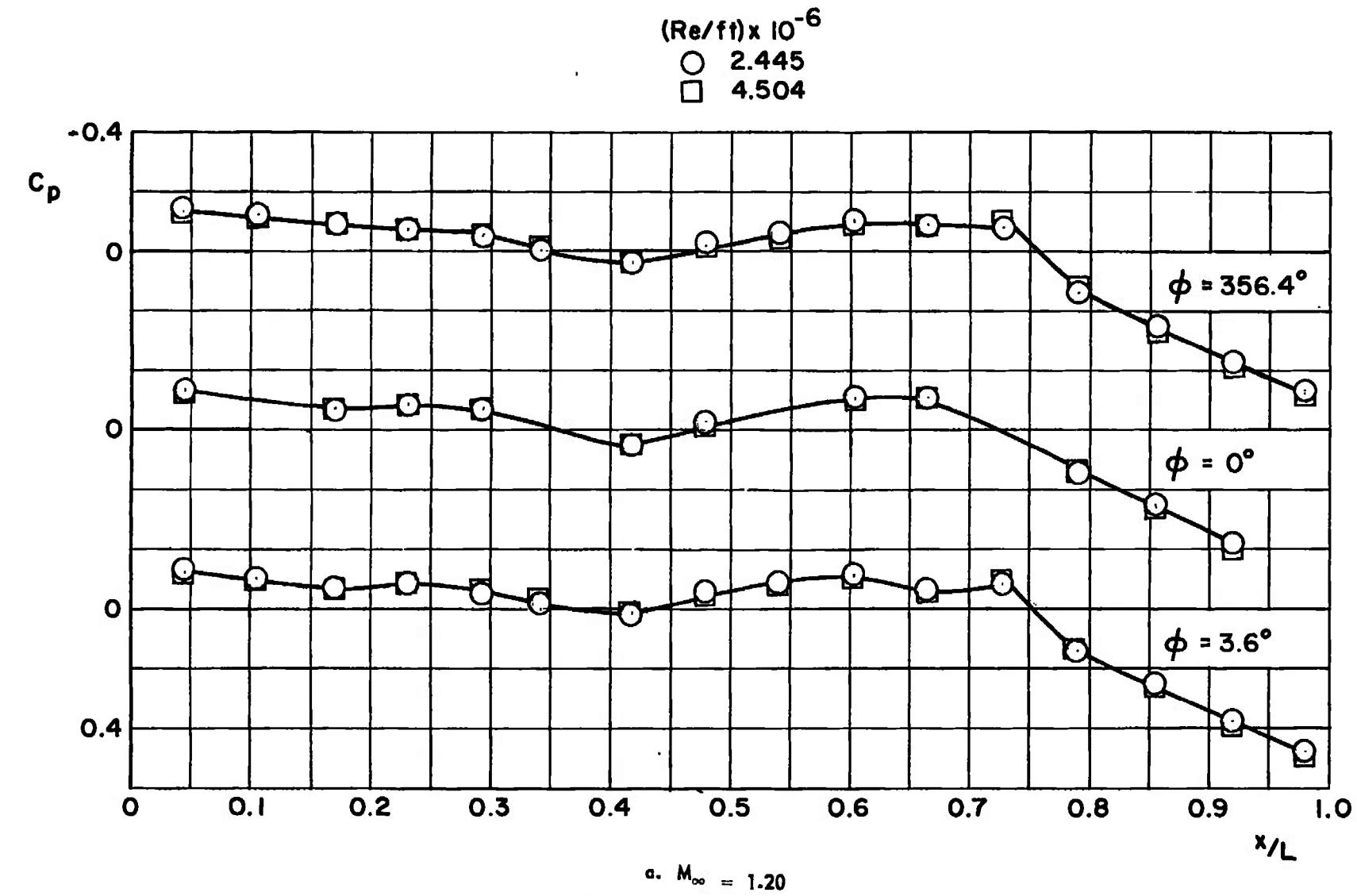


Fig. 19 Variation of Pressure Coefficient along the Pressure Panel

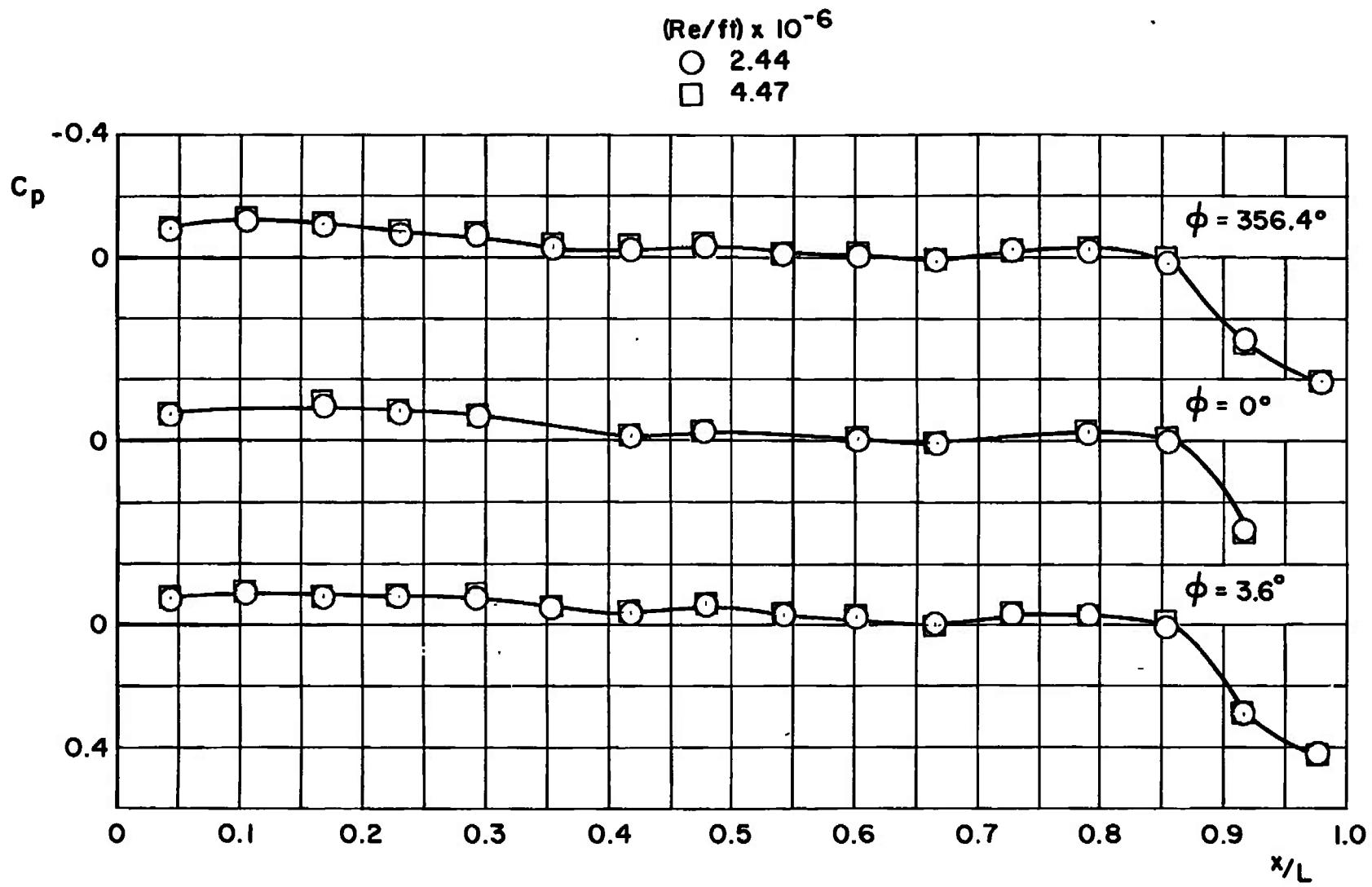
b. $M_\infty = 1.30$

Fig. 19 Continued

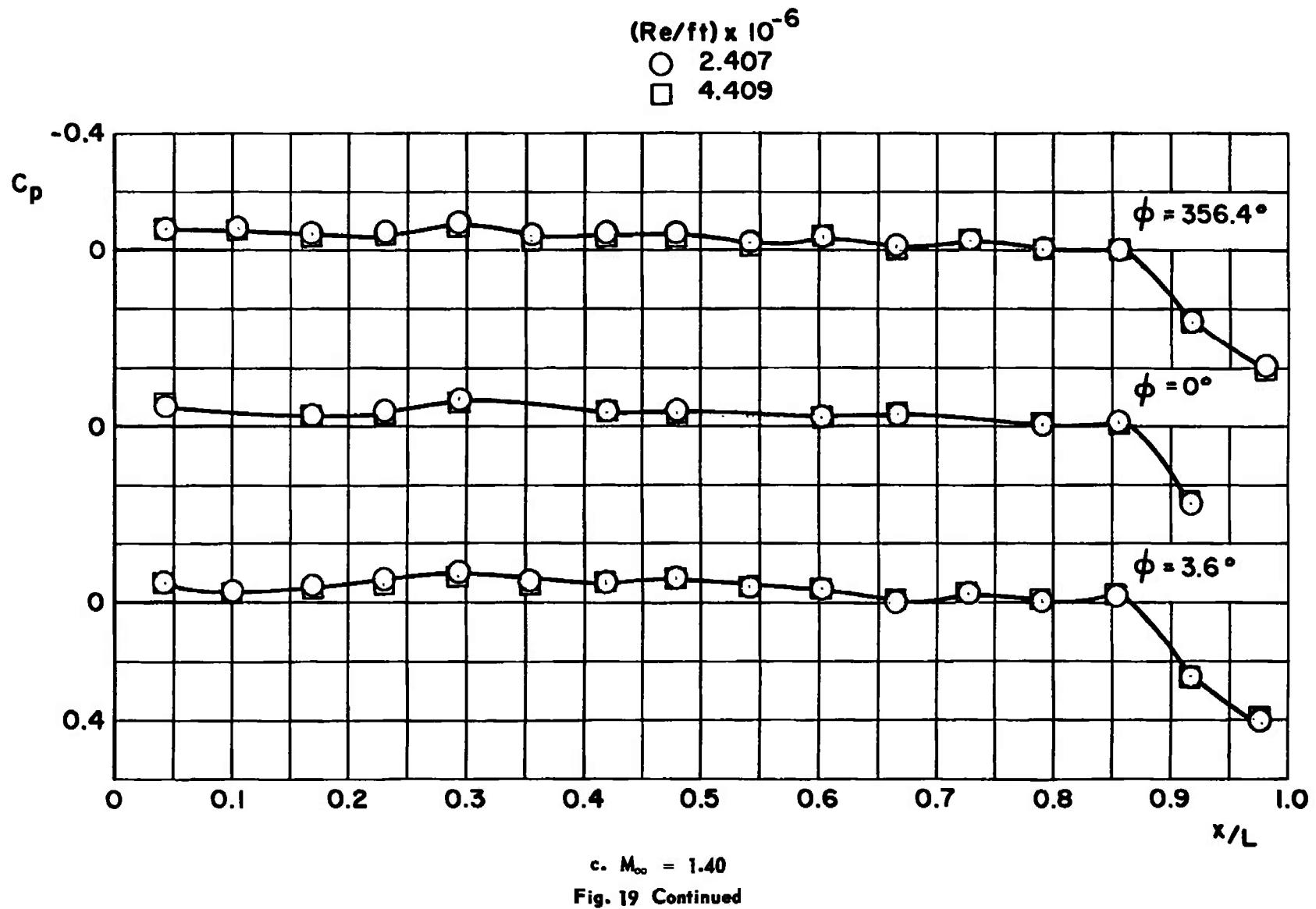
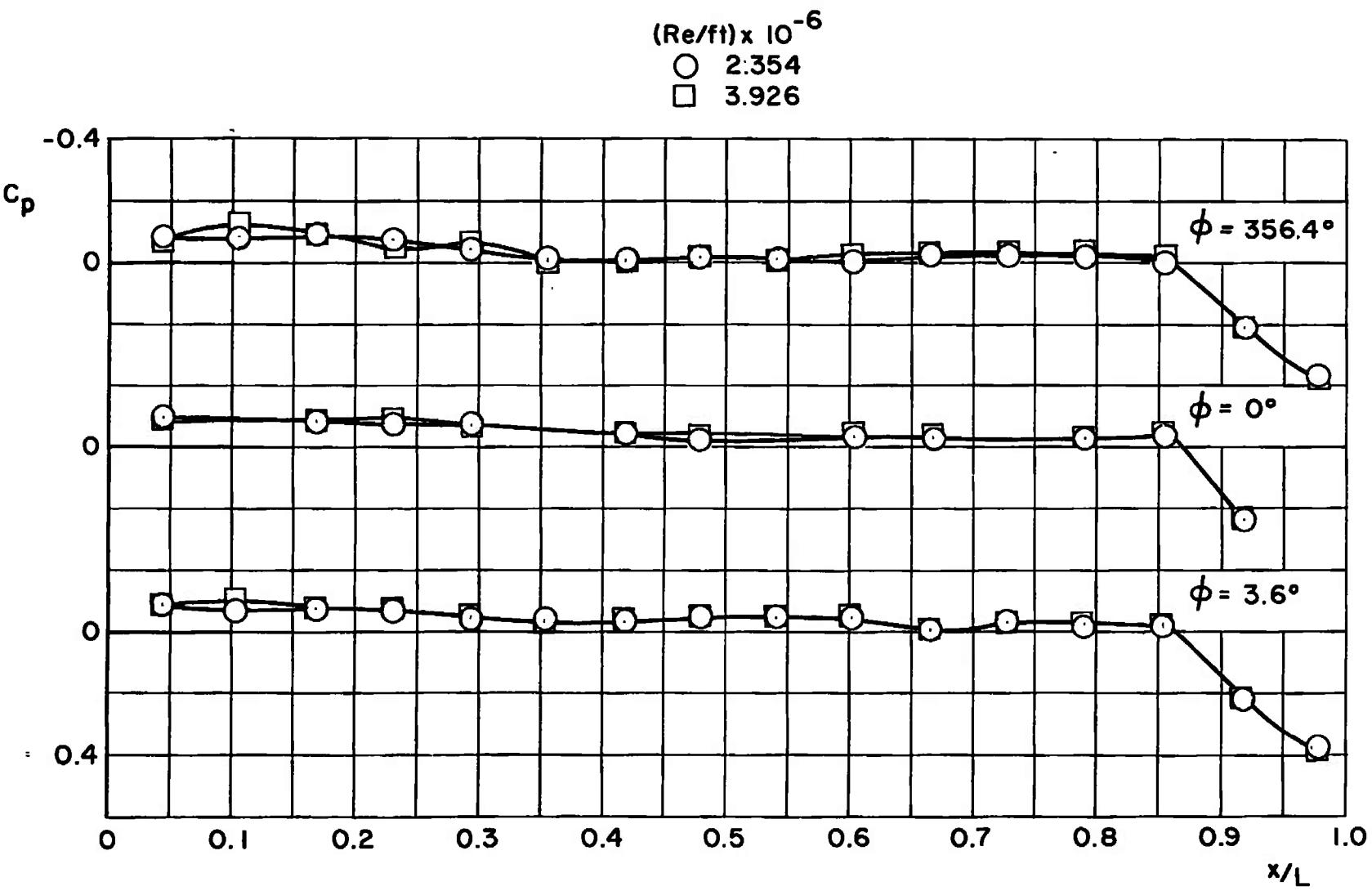


Fig. 19 Continued



d. $M_\infty = 1.50$
Fig. 19 Continued

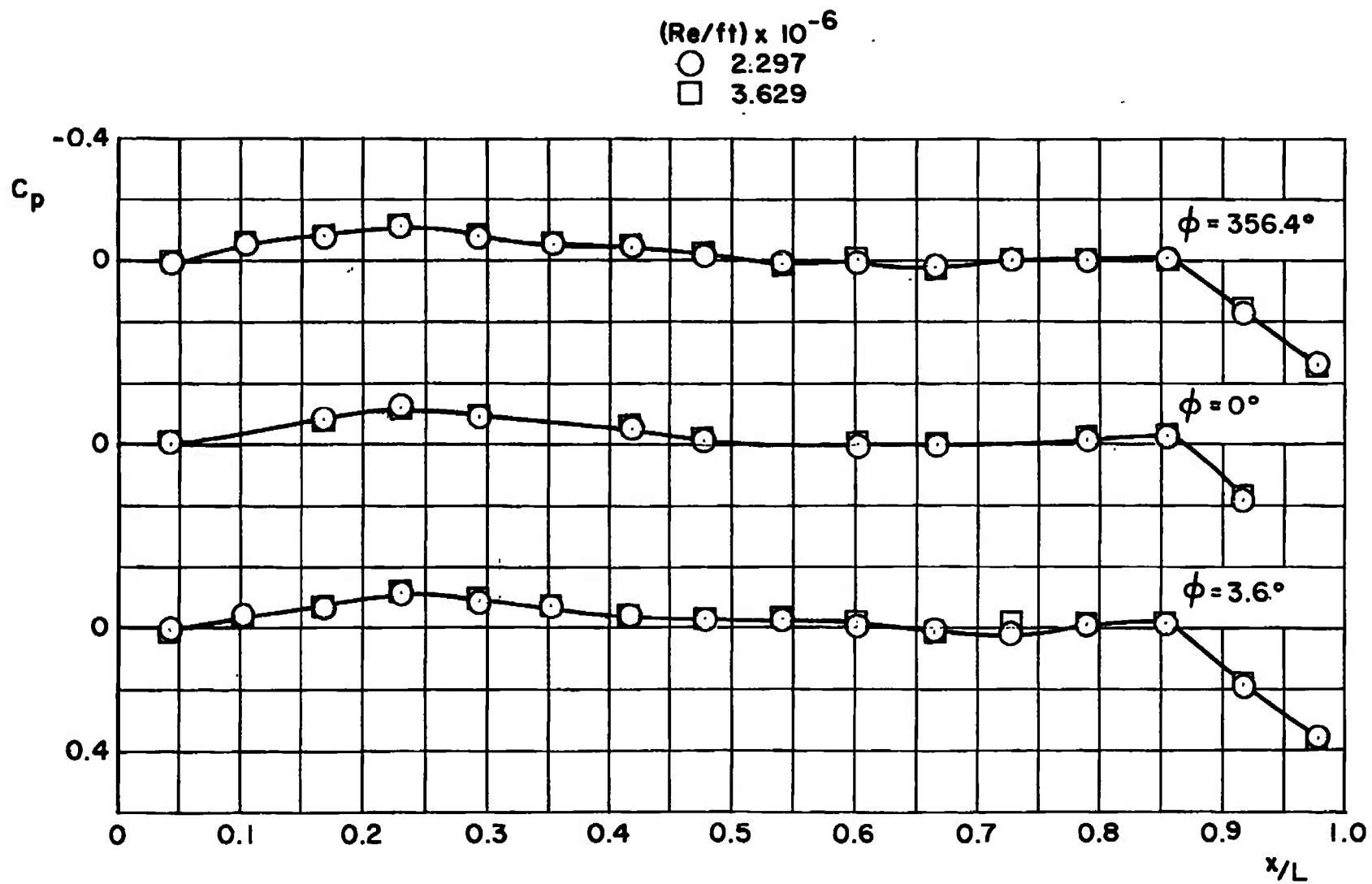
e. $M_\infty = 1.60$

Fig. 19 Concluded

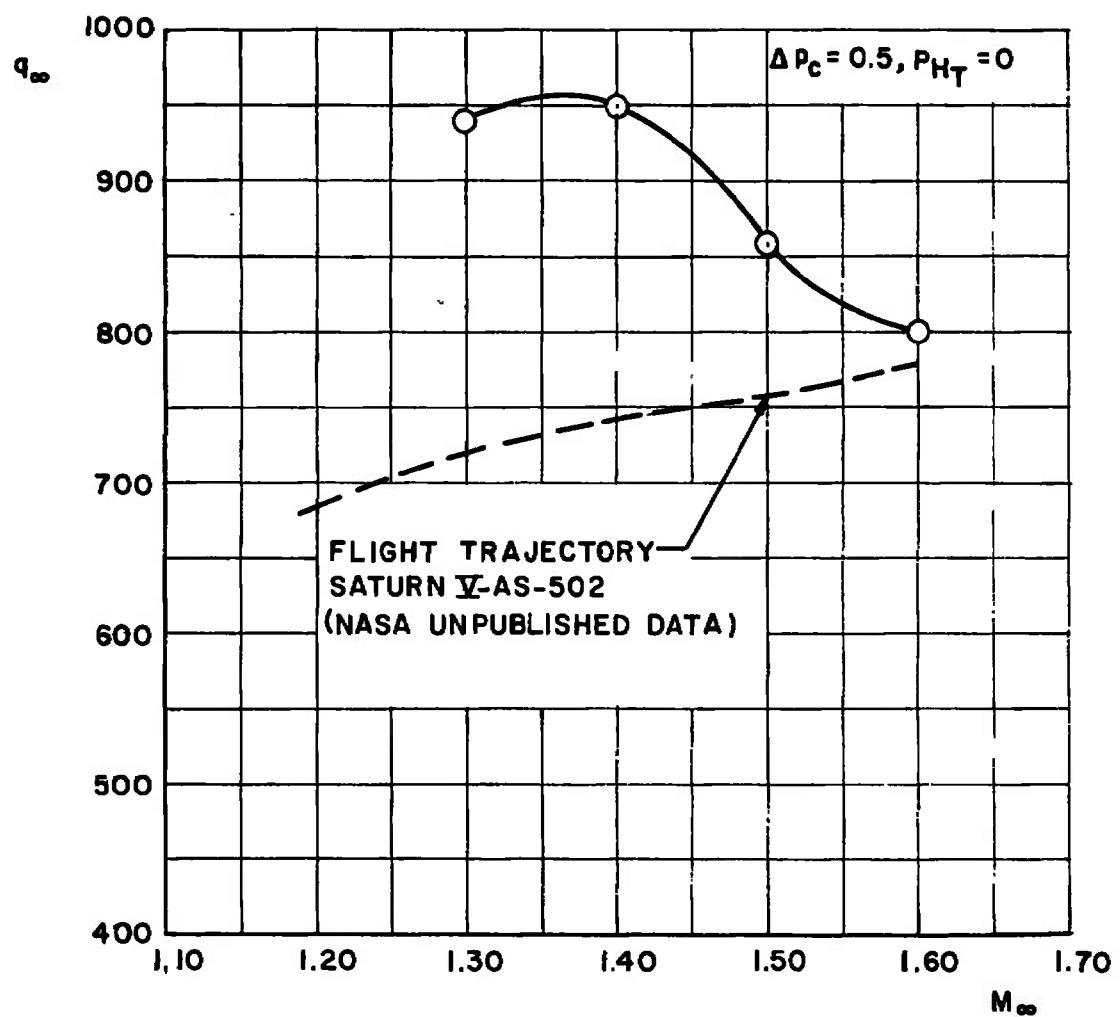


Fig. 20 Variation of Maximum Dynamic Pressure with Mach Number for Flutter Phase

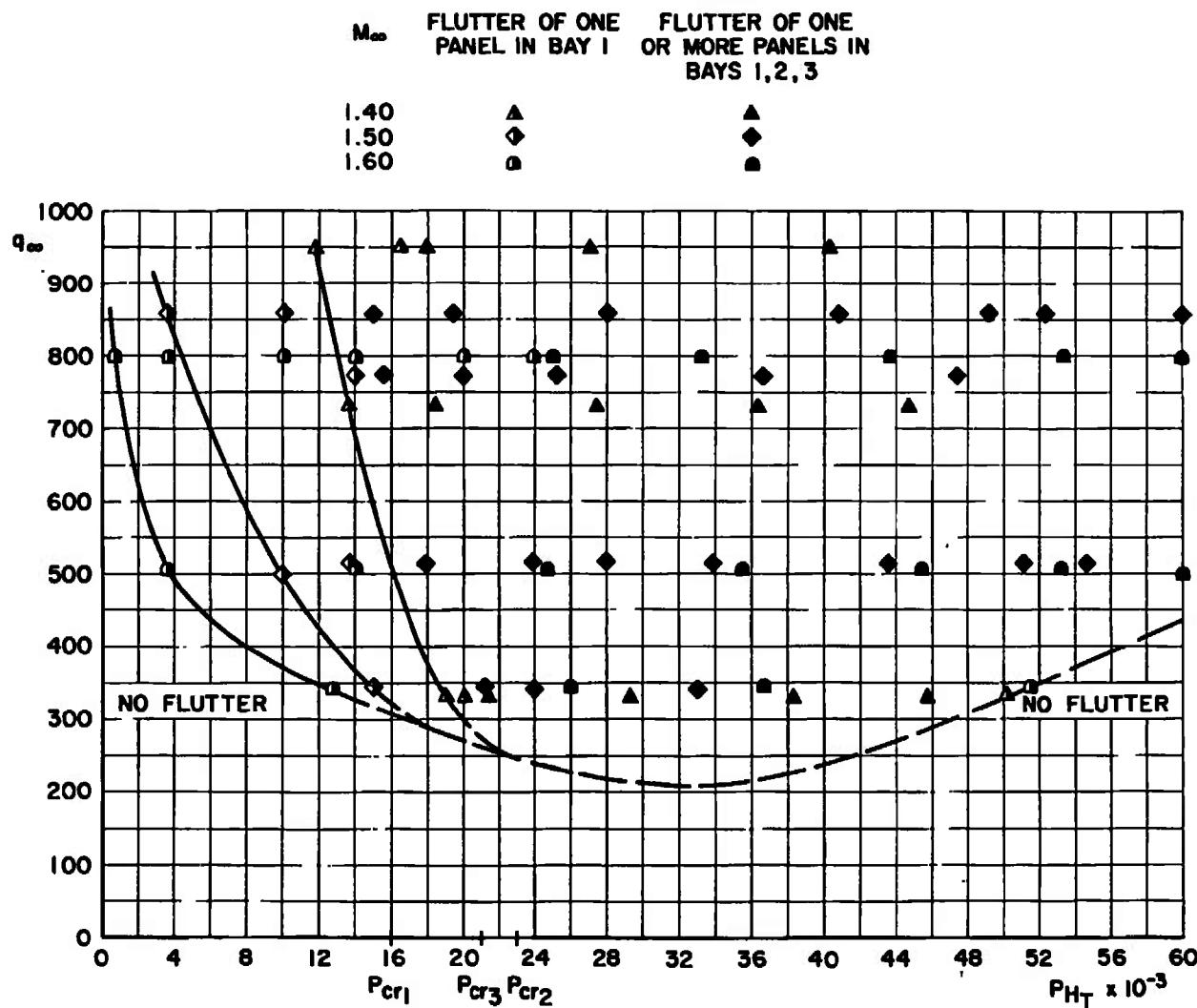


Fig. 21 Variation of Dynamic Pressure with Axial-Compressive Panel Load for $\Delta p_c = 0.50$ psi

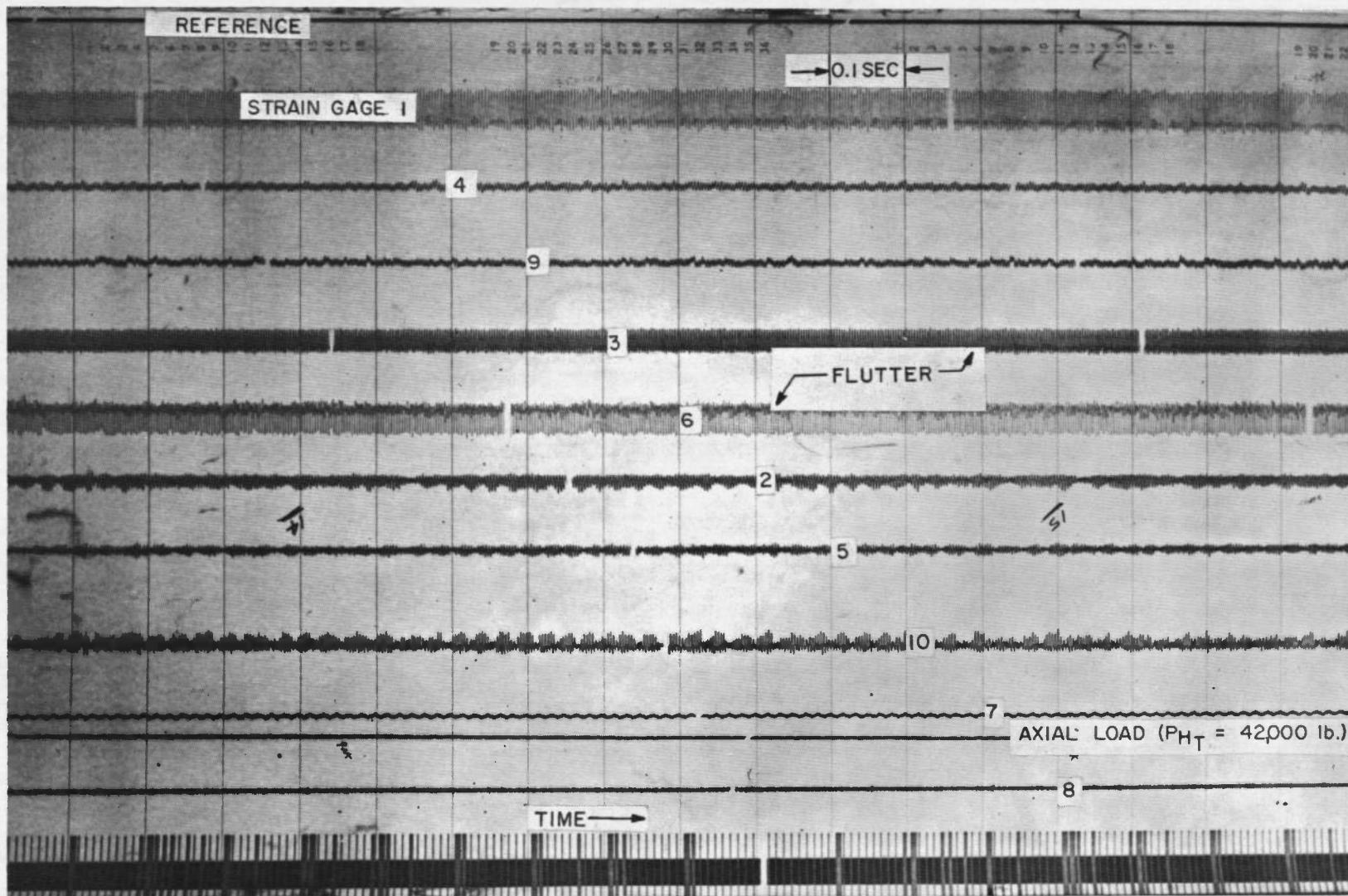


Fig. 22 Oscillograph Trace Showing Panel Flutter

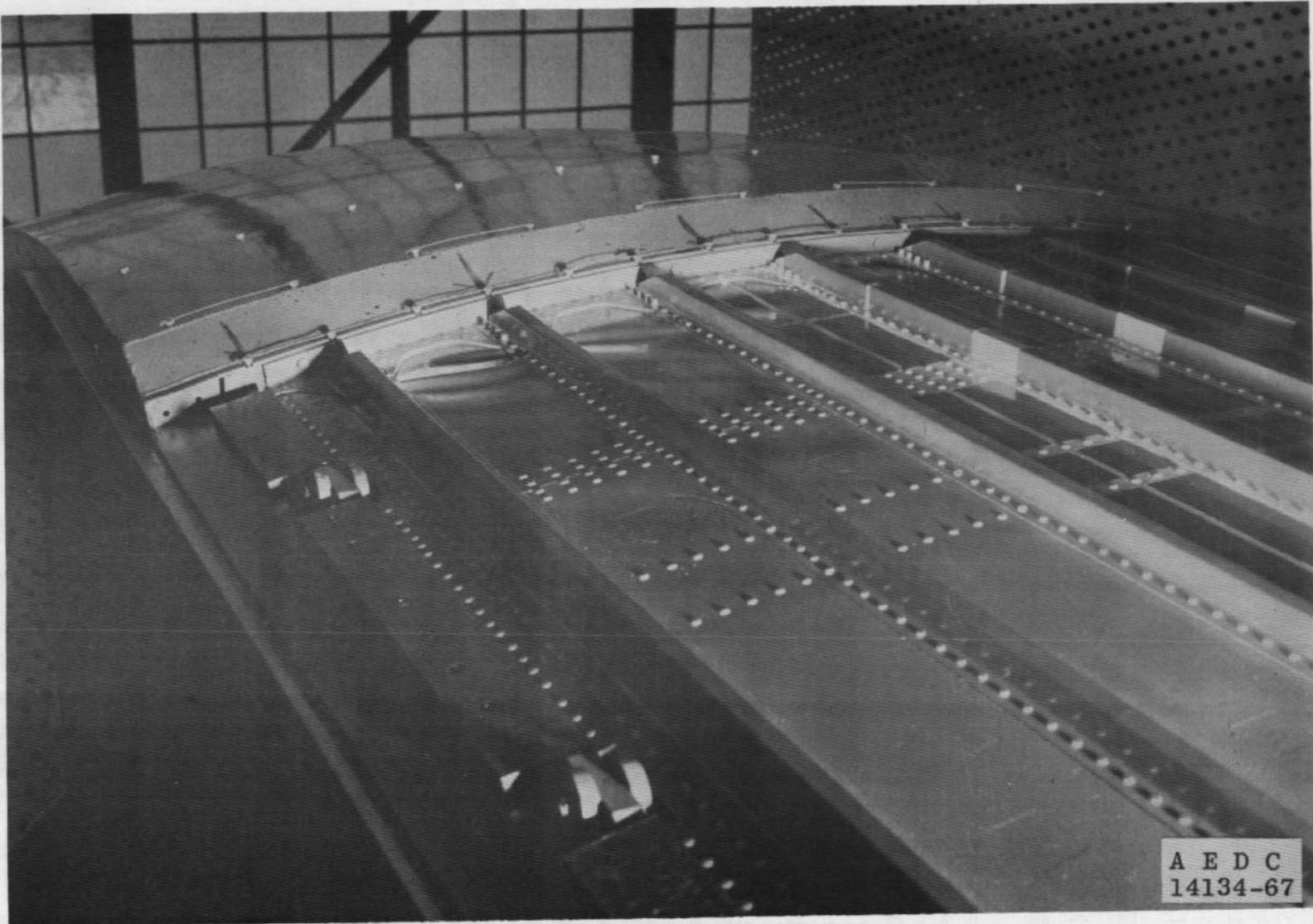


Fig. 23 Photograph of Flutter Panel Showing Damaged Panels

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13. ABSTRACT Flutter characteristics of a 30-deg segment of the full-scale Saturn S-IVB stage were obtained at Mach numbers from 1.30 to 1.60 for various combinations of axial-compressive loads and panel differential pressures. Flutter was encountered in one or more panels when sufficient axial load was applied to either partially or completely buckle the panels. The flutter was amplitude limited, and no structural failures occurred on any of the panels as a result of flutter. However, the test had to be terminated when two panels in the fifth bay were statically buckled beyond their elastic limit and permanent deformation resulted. A calibration test was conducted prior to the flutter test to determine the optimum design of the fixture used to support the model. Also static-pressure and boundary-layer surveys were made on the model at tunnel conditions comparable to those of the flutter phase.		
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